Permeable Reactive Walls

NFESC

Chuck Reeter or Jed Costanza

Battelle

Arun Gavaskar, Neeraj Gupta, or Bruce Sass

Agenda – Topics on Permeable Reactive Walls

- **NFESC (10 min)**
  I. **Background**
- **Battelle (45 min)**
  II. Basic Principles
  III. Reactive Wall Design
  IV. Wall Construction Technologies
  V. Monitoring The Wall
  VI. Estimated Costs
- **NFESC (35 min)**
  VII. Navy Demonstration Sites
  VIII. Technology Summary
- **References/TAT Info**

I. Background

- Background
- Permeable reactive wall
- Conceptual diagram
- Regulatory setting

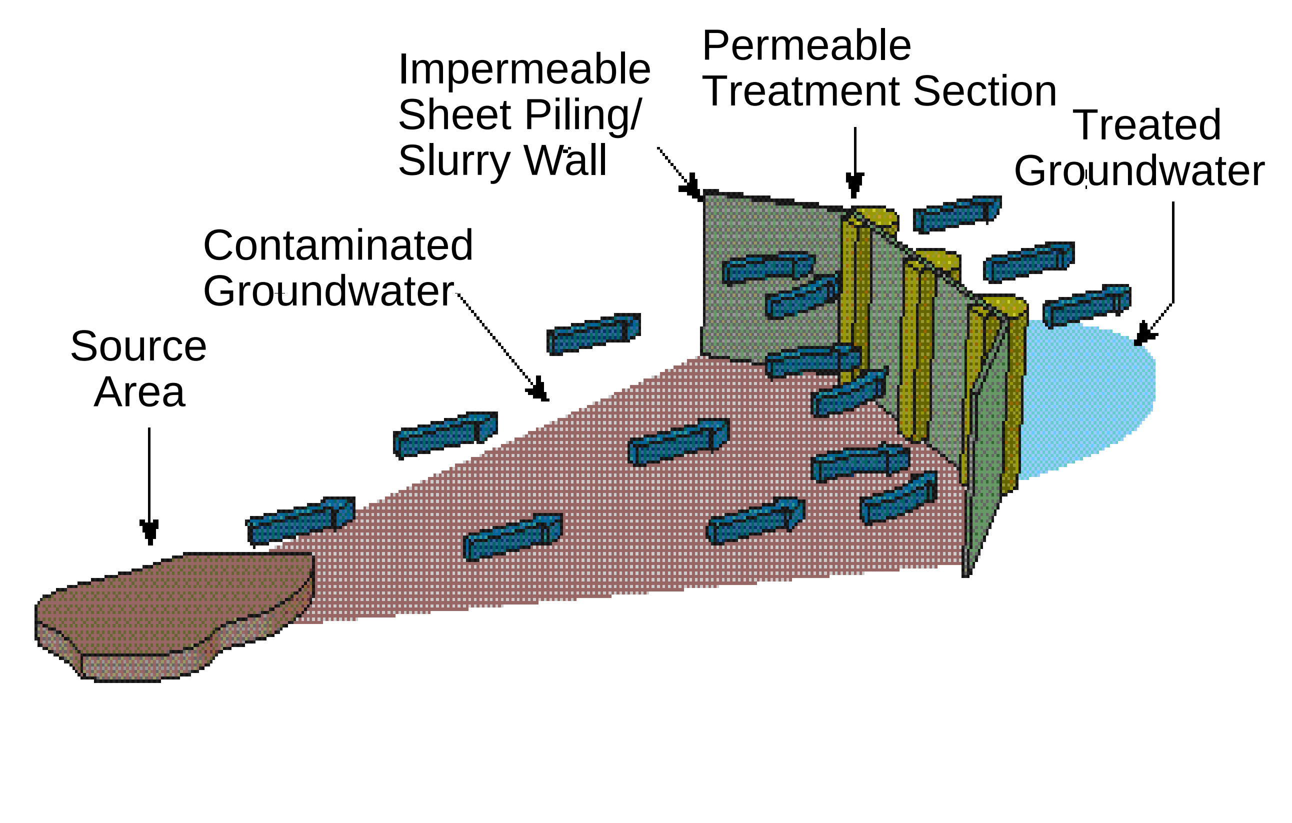
Background

- EPA estimates over 5,000 chlorinated solvent-contaminated sites (including TCE and PCE) at DoD, DOE, Superfund facilities.
- Most common method for remediation of contaminated groundwater is pump-and-treat. Innovative technologies needed to minimize remediation costs.
- EPA estimates that permeable reactive walls can be used at 10 to 20% of these contaminated sites. Groundwater remediation costs can be significantly reduced.
- Approximately 15 pilot and full-scale permeable wall projects are under way in the U.S. and are being monitored by the EPA RTDF Permeable Barriers Action Team.

What Is a Permeable Reactive Wall?

- Remediates VOCs and/or metals in groundwater to below MCL concentrations or to non-detect using a reactive media
- Passive remediation technology using natural groundwater flow properties (no external energy source is needed)
- No aboveground structures are required
- Low operation and maintenance
- Usually more cost-effective than a pump-and-treat system
- Can be used in most heterogeneous geologic locations

Conceptual Permeable Reactive Wall



Sometimes configured as a funnel-and-gate system

Regulatory Setting

- Regulators are now more cognizant of cost benefits of innovative technologies, such as permeable walls - EPA RTDF, SITE program
- Interstate Technology Regulatory Commission (ITRC) has set up a Permeable Barriers Group to recommend general guidelines for PRW design and monitoring
- Generally, need federal and/or state regulatory support early in the remedial selection process

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II. Basic Principles

- Reactive wall uses
- Installation difficulties
- Reactive materials
- Dechlorination reaction

When Do You Use a Permeable Reactive Wall?

- For in situ treatment or detoxification of groundwater contaminant plumes
- Permeable walls have been used for treatment of dissolved contaminants, including:
  - Chlorinated solvents, such as perchloroethene (PCE), trichloroethene (TCE), dichloroethene (DCE), and others
  - Metals, such as chromium, uranium
  - VOCs, such as BTEX and others
- Alternative to pump-and-treat

When Is It Difficult (But Not Impossible) to Use Permeable Walls?

- Plume is very wide (cost issue)
  - Walls over 1,000 ft long
- Plume is very deep (cost issue)
  - 40-50 ft with conventional techniques
  - Innovative construction methods for greater depths
- Aquitard is very thin (difficult to key in)
- Underground utilities (extra precautions required)
- Groundwater velocity is very low or very high

What Types of Reactive Materials Are Used in a Permeable Reactive Wall?

- The most common so far has been granular iron, which is a strong reducing agent (iron sample)
  - Abiotically reduces PCE, TCE, DCE to ethene and ethane
  - Reduces hexavalent chromium to trivalent chromium
- Socks containing magnesium dioxide
  - Aerobic conditions for microbial degradation of BTEX
- Peat moss and carbon particles for VOCs (usually high maintenance)

Dechlorination (Reduction) Reaction

Hydrogenolysis pathway: (forms DCE and vinyl chloride intermediates, which themselves degrade to ethene and ethane)

$$Fe^{0} + X\text{-}Cl + H^{+} \longrightarrow Fe^{++} + Cl^{-} + X\text{-}H$$

Beta-elimination pathway: (intermediates are short-lived)

$$X\text{-}Cl \longrightarrow \underset{\text{(intermediates)}}{\text{Alkynes}} \longrightarrow \text{Ethene} + Cl^{-}$$

Technology initially researched and tested at the University of Waterloo, Canada, in the early 1990s. Patented by EnviroMetals Technologies, Inc. (ETI)

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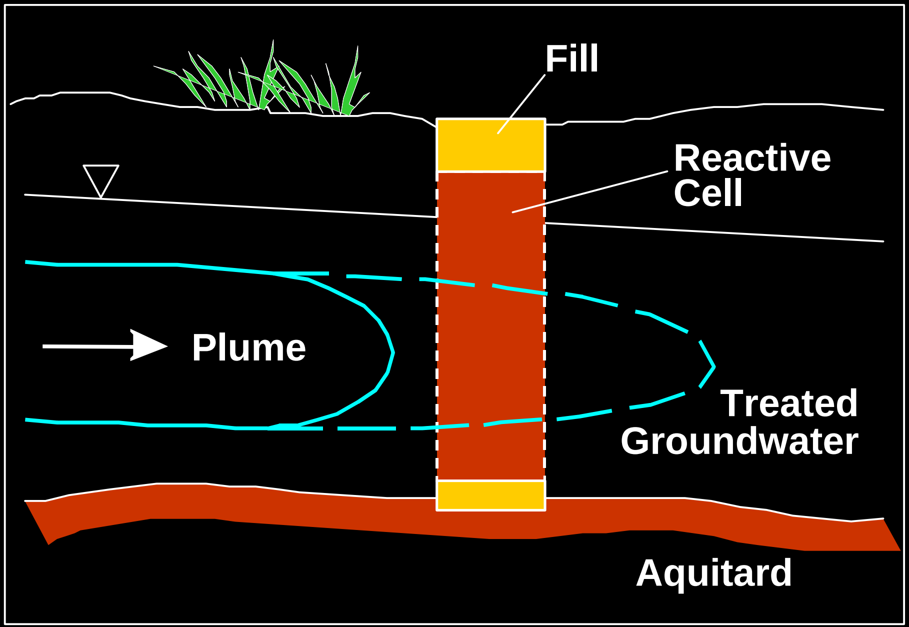
III. Reactive Wall Design

- Design configurations
  - Continuous wall
  - Funnel-and-gate
  - Hanging wall
- Design steps
  1. Site characterization
  2. Treatability testing
  3. Modeling
     - Hydrogeologic
     - Geochemical

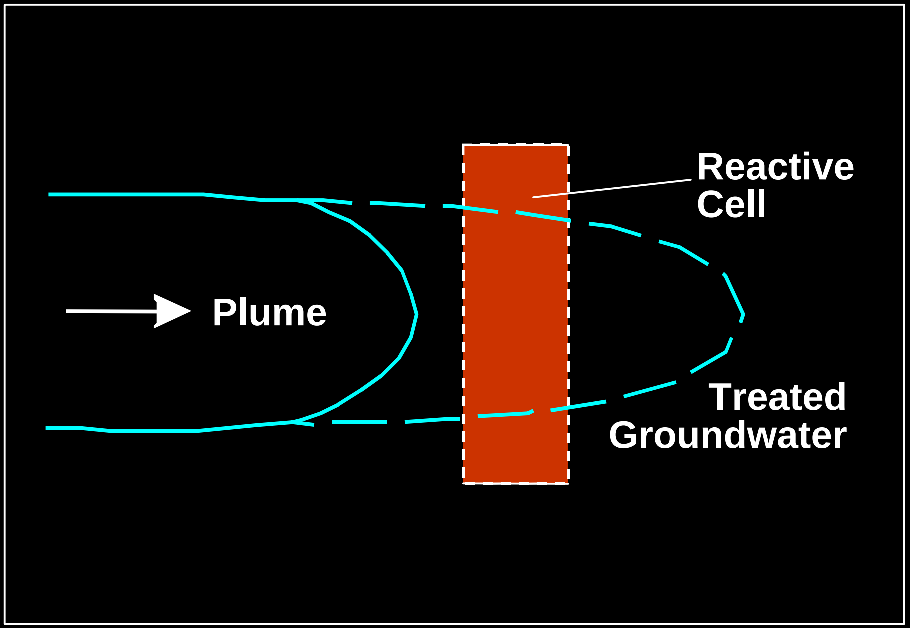
What Are the Different Permeable Wall Configurations?

- Continuous reactive barrier
- Funnel and gate (multiple gates)
  - Funnel is the impermeable section of the wall
  - Gate is the permeable section
  - Allows better control over capture of contaminants
- Hanging wall (not keyed into the aquitard)
  - May not be suitable in many cases because contamination could flow underneath (DNAPLs)

Continuous Wall

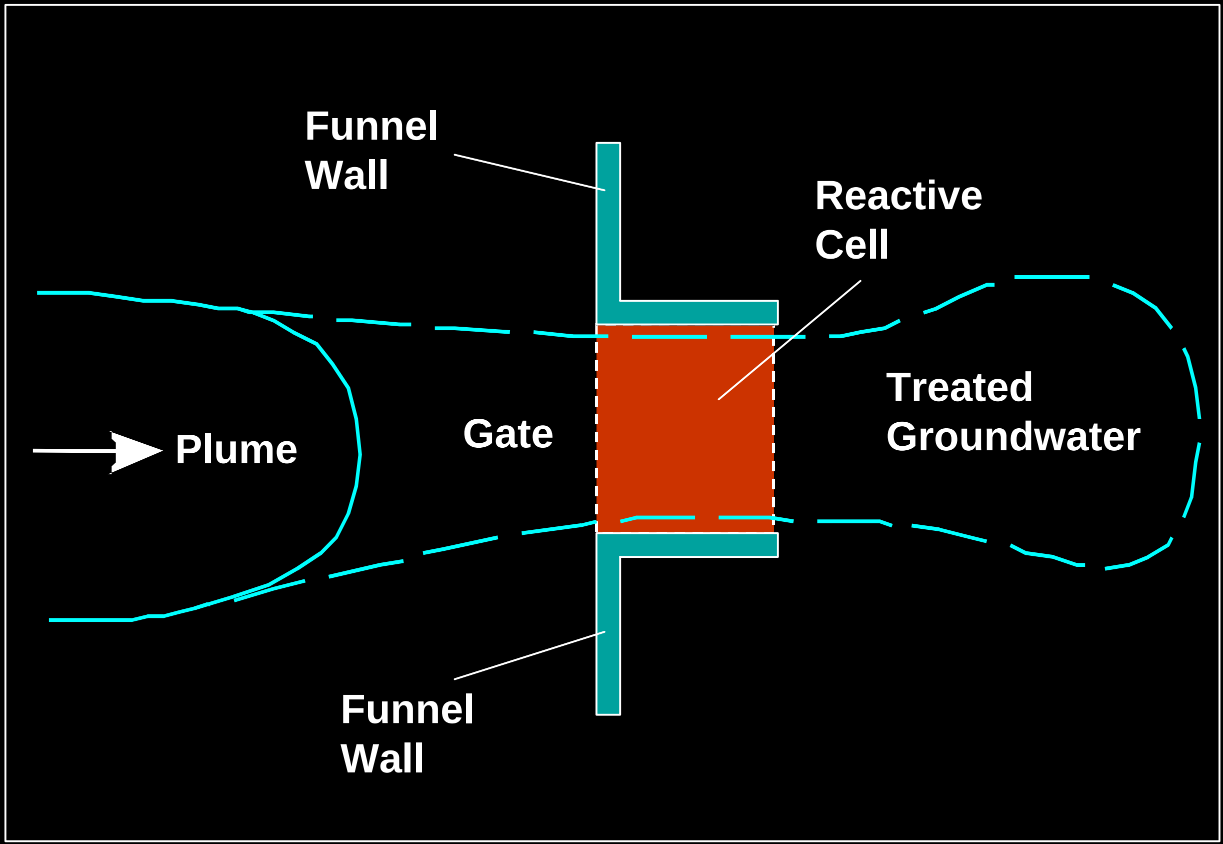


(a) Elevation View of a Permeable Barrier



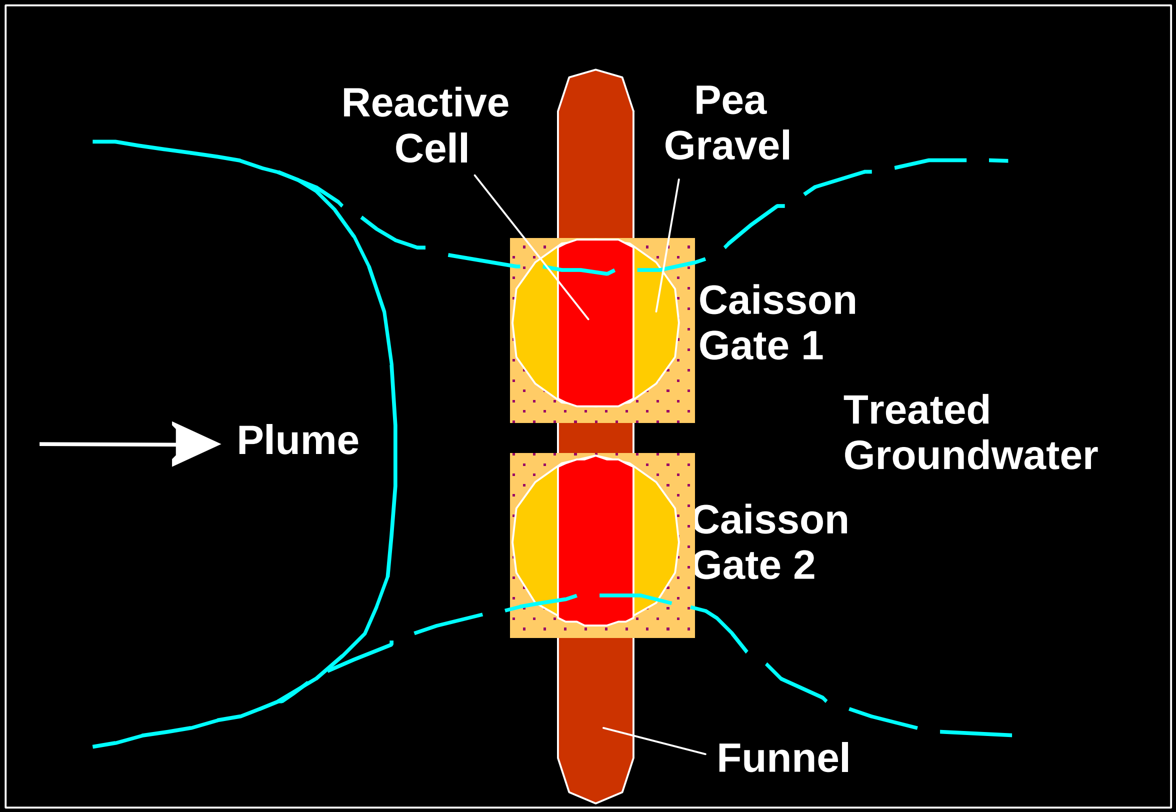
(b) Plan View of a Continuous Reactive Barrier Configuration

Funnel-and-Gate (Single Gate)



(c) Funnel-and-Gate System (Plan View)

Funnel-and-Gate (Double Gate or Wall)



(d) Funnel-and-Gate System with Two Caisson Gates (Plan View)

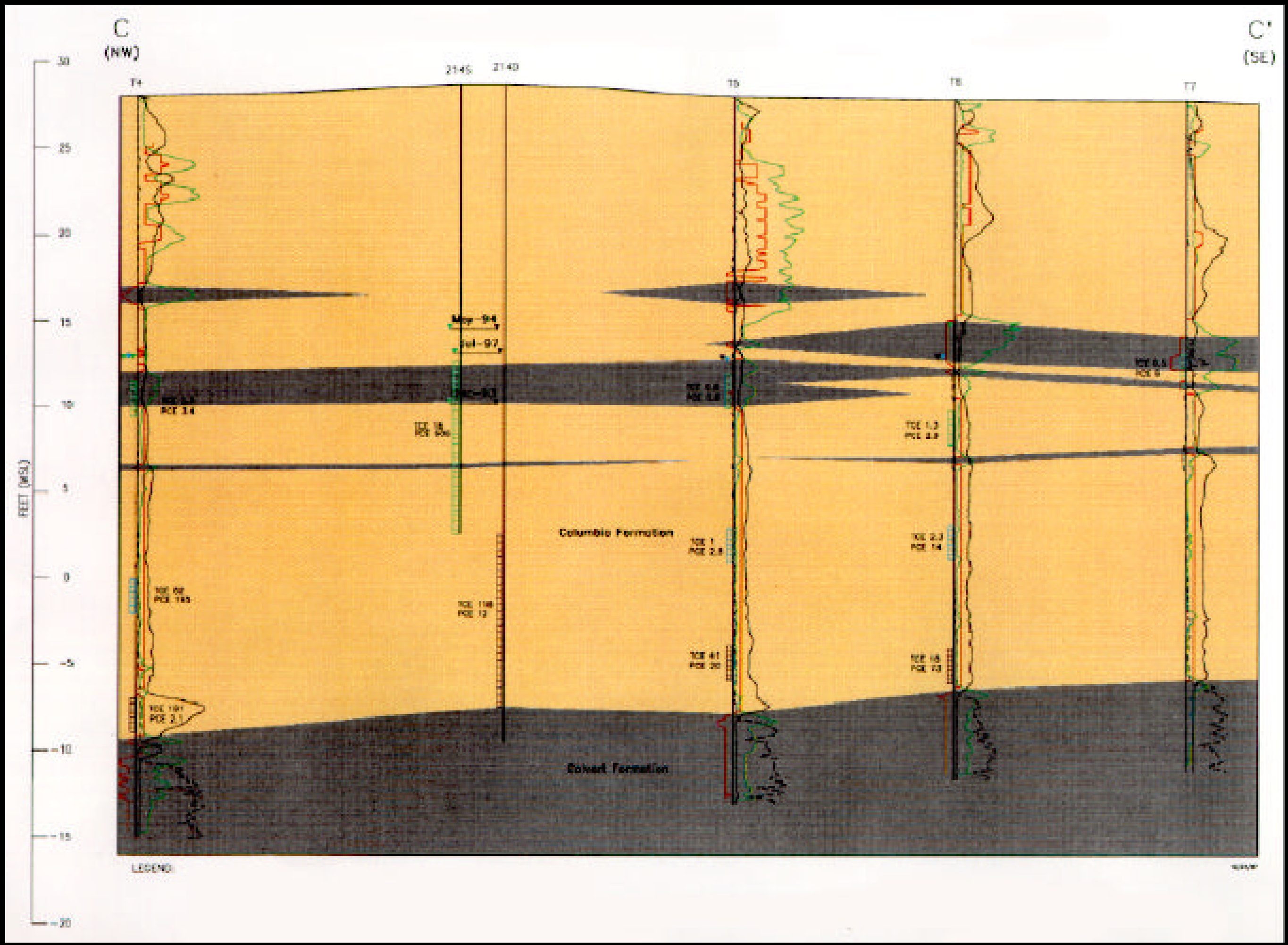
Design Step Number 1 – Site Characterization (An Important Aspect)

- Unlike a pump-and-treat system, a permeable wall cannot be relocated or reconfigured easily
- Contaminant types and distribution
- Hydrogeology (location and dimensions of wall)
  - Groundwater table, aquitard depths, fluctuations
  - Hydraulic conductivity and porosity
  - Groundwater flow velocity and direction
- Groundwater geochemistry (longevity of wall)
  - Ca, Mg, pH, alkalinity, dissolved oxygen (can cause precipitation on the reactive medium)

Site Characterization – Dover AFB, DE

CPT Rig

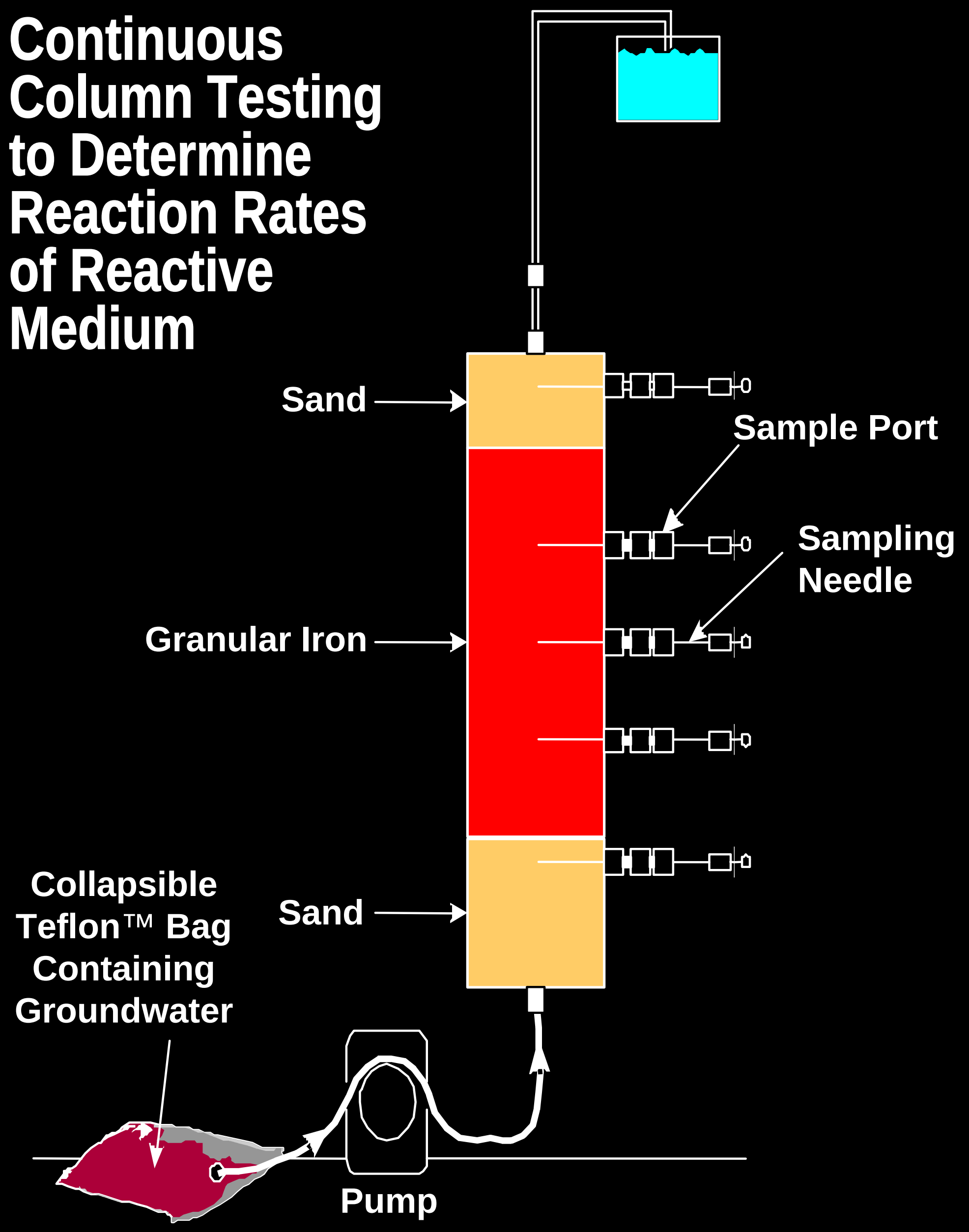
Geologic Cross Section – Dover AFB, DE

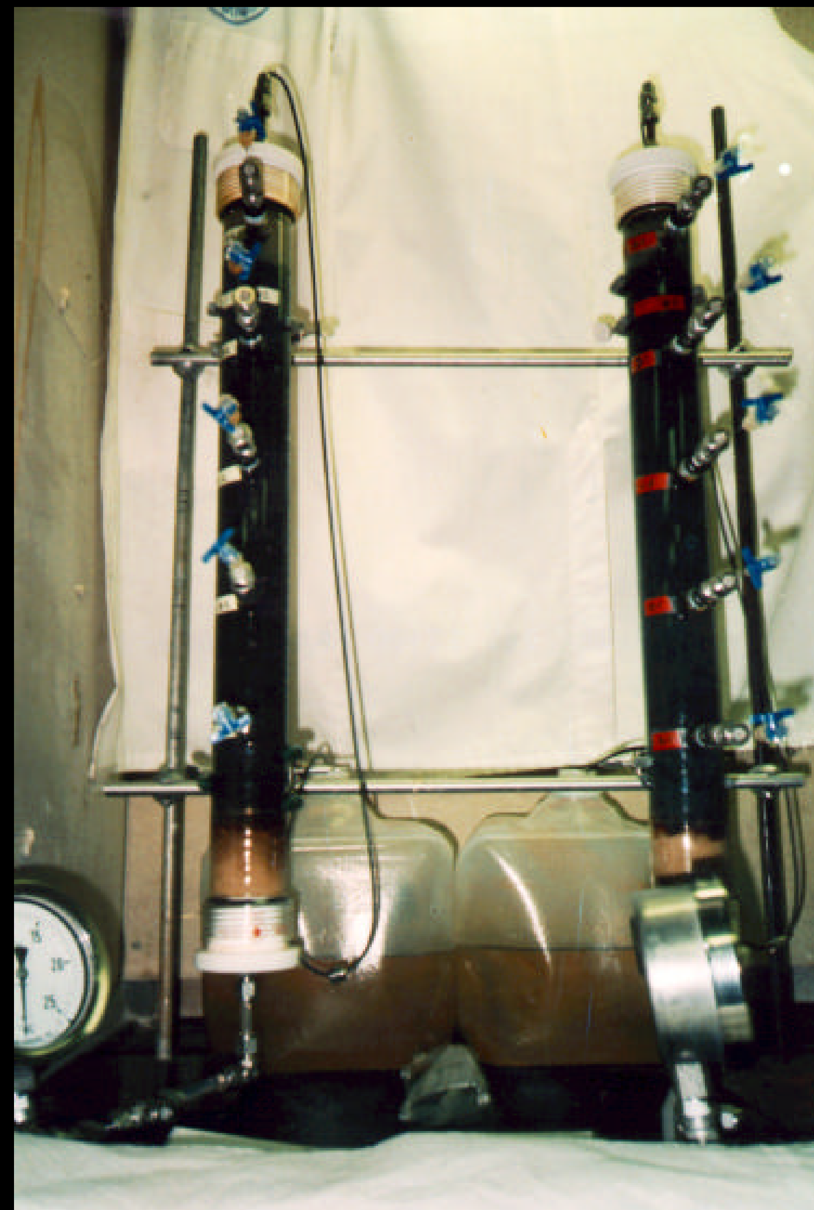


Design Step Number 2 – Treatability Testing

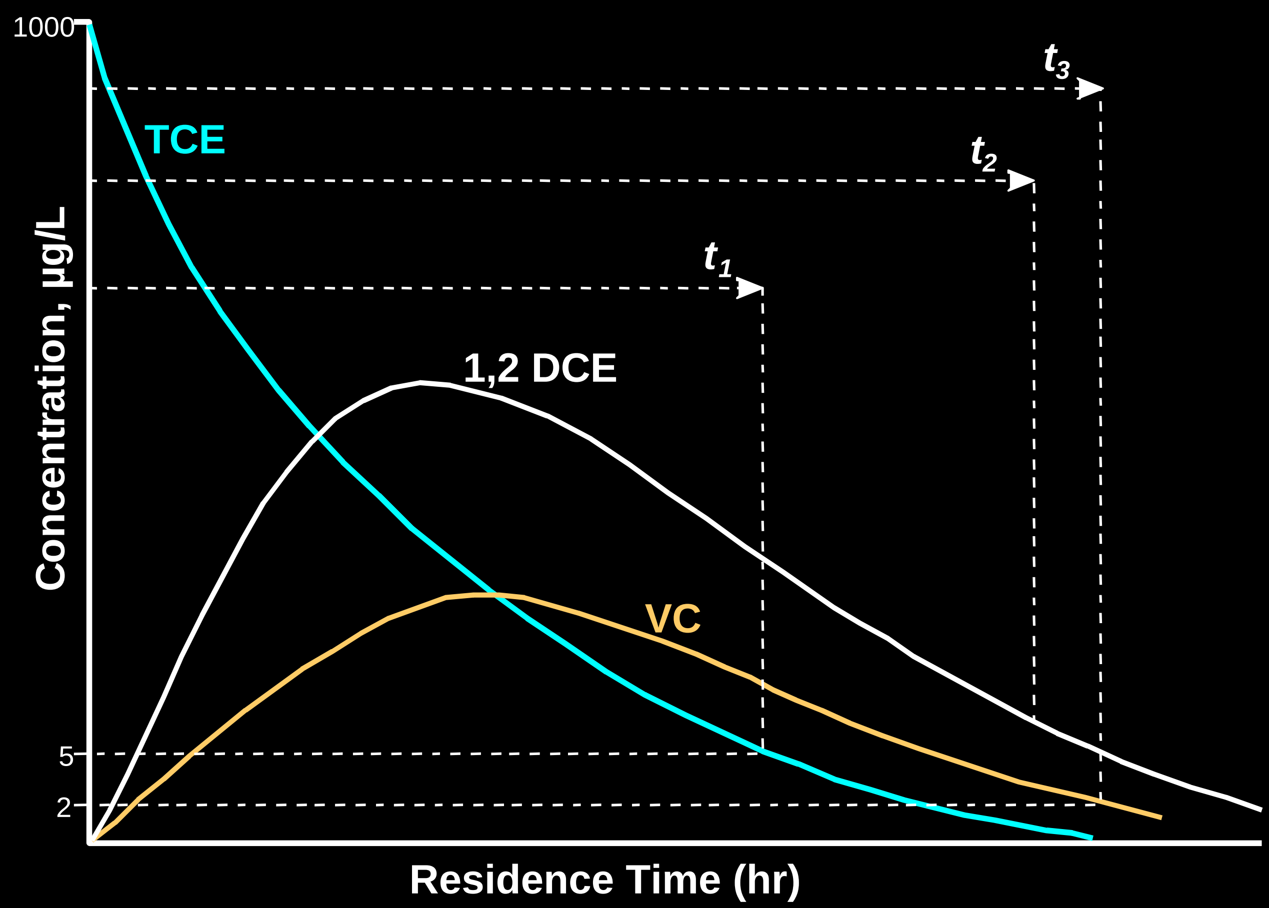
- Required to determine degradation rate of PCE, TCE, DCE, VC, or other contaminants under site-specific conditions
- Helps in identifying conditions that may affect the longevity of the reactive medium
- Batch tests can be done, but continuous column tests are most useful and common

Continuous Column Testing to Determine Reaction Rates of Reactive Medium





Column Test Data – Dover AFB, DE

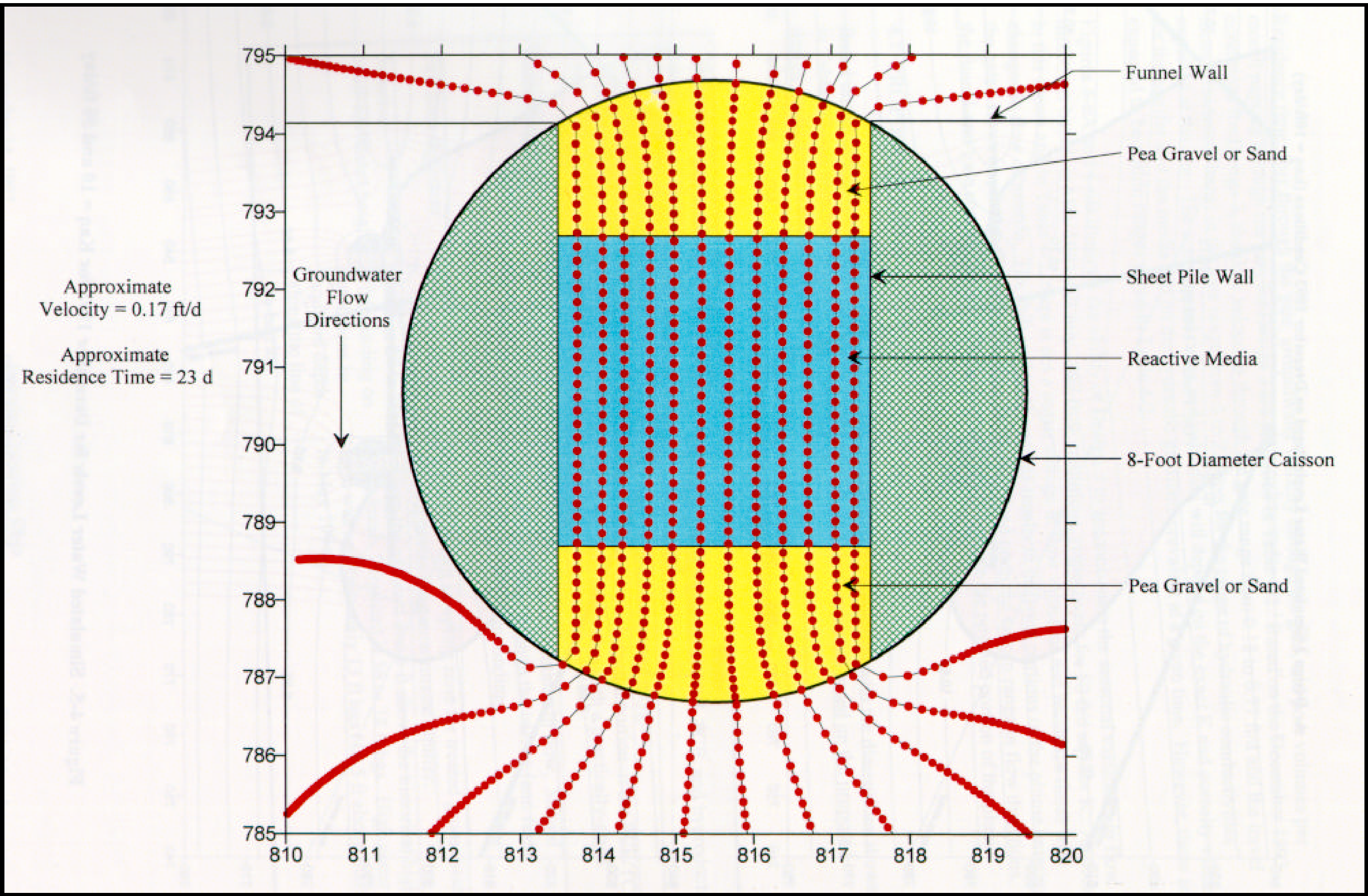


[t_3 is the required residence time]   [not to scale]

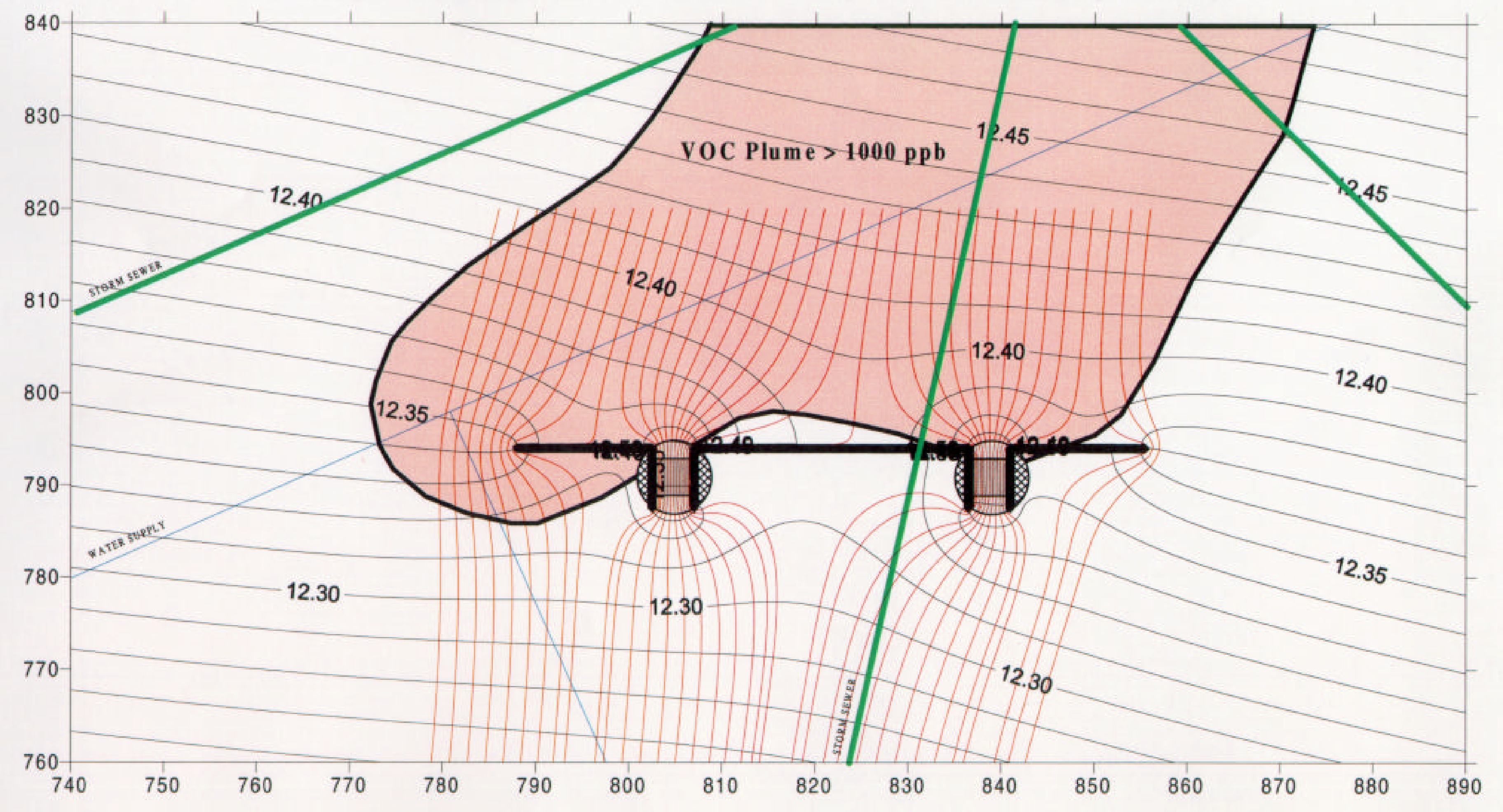
Design Step Number 3 – Modeling

- Set up a hydrogeologic model of groundwater flow field
- Model different barrier configurations
- Model indicates width of barrier or gate required to capture the plume
- Model indicates projected groundwater velocity through the reactive medium
- Helps to determine gate thickness
- Aids monitoring system design

Paths and Travel Times Through Permeable Barrier



Simulated Water Levels (Seasonal Variations) – Dover AFB, DE



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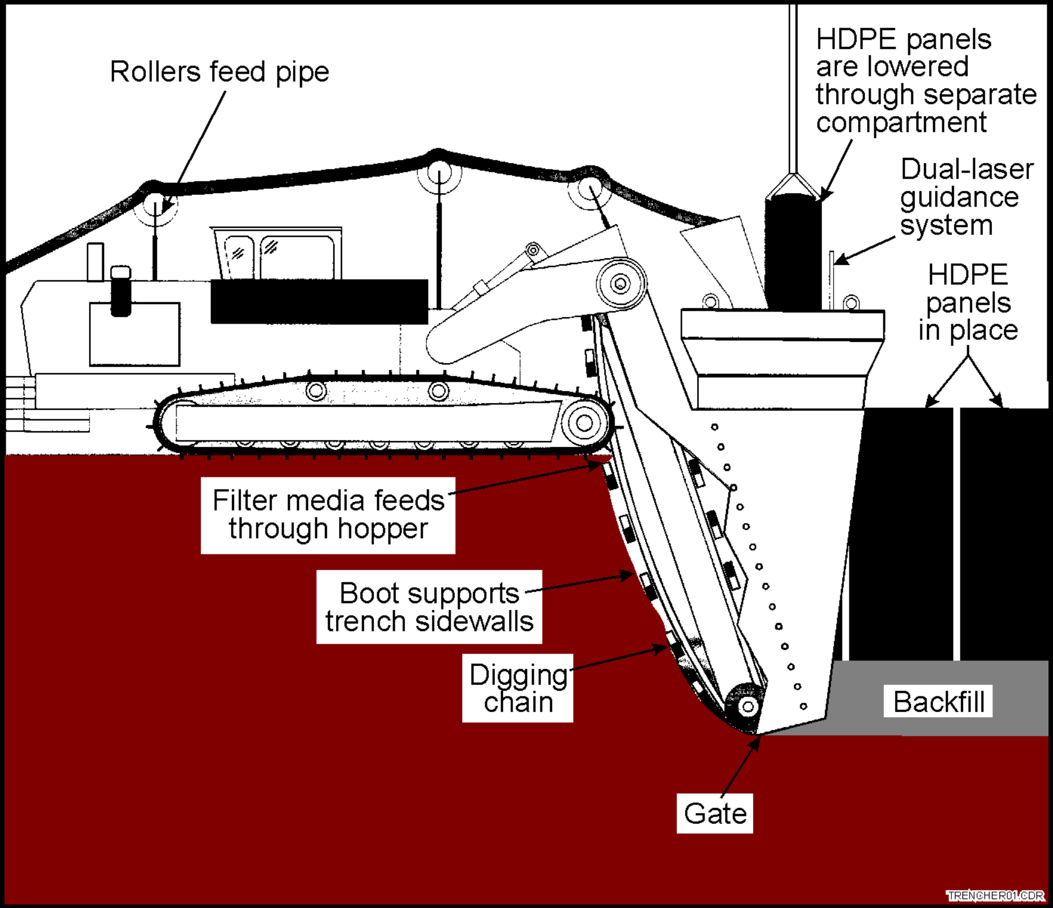
IV. Construction Technologies

- Reactive cells (gates)
  - Trench-type reactive cell
    - Backhoe (down to 25- or 30-ft depth)
    - Clamshell (deeper installations)
    - Continuous trencher (new device)
  - Caisson-type installation of reactive cell
  - Other (pressure jetting, deep soil mixing)
- Impermeable funnel walls
  - Cement/soil-bentonite slurry walls
  - Sheet piling (interlocking or sealable joints)

Construction of a Permeable Gate by Trenching – GE/Intersil Site – Sunnyvale, CA

Construction by Continuous Trenching – U.S. Coast Guard Site – Elizabeth City, NC



Continuous Trencher in Operation

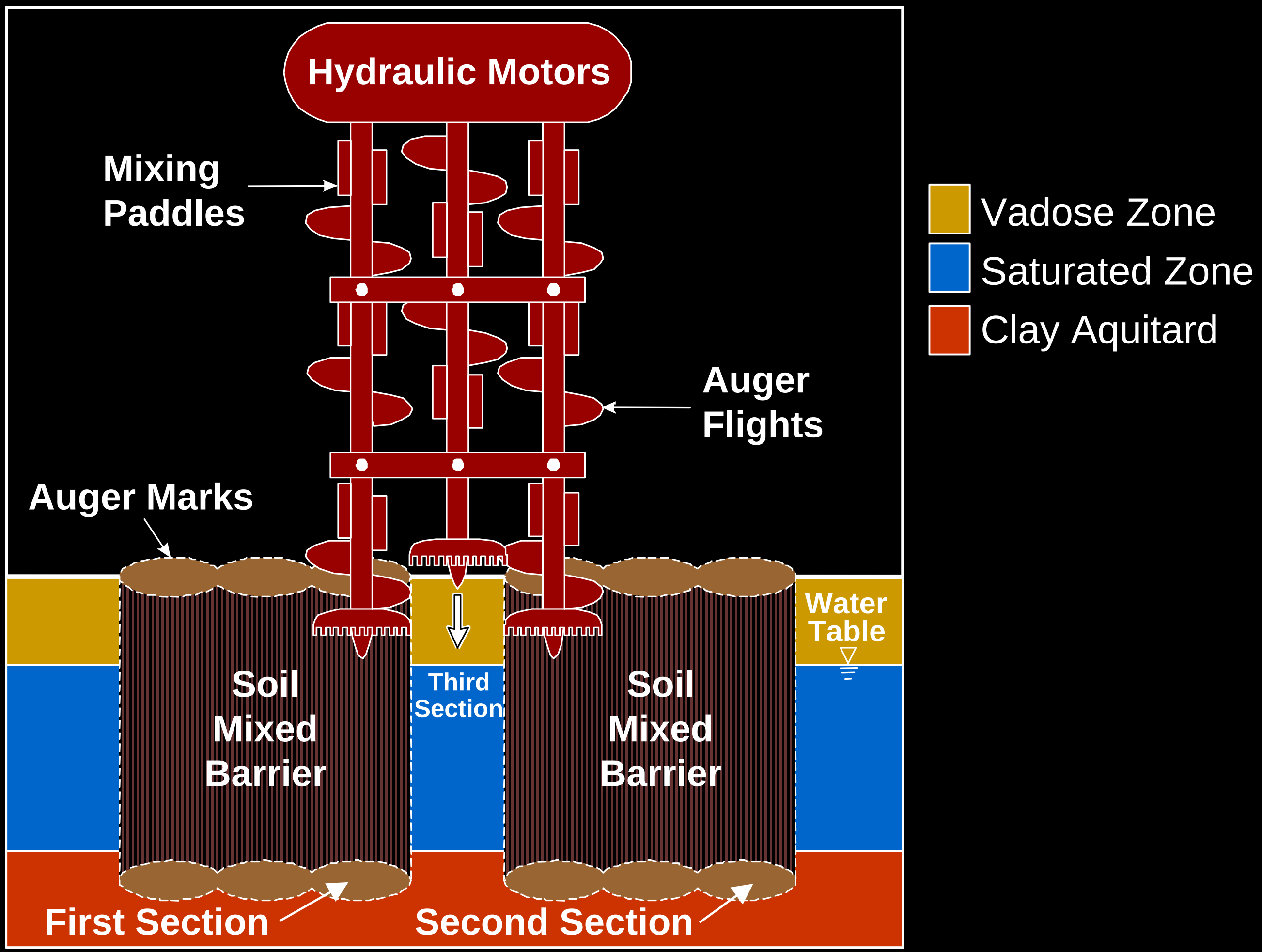
Installation of Granular Iron in the Gate (Reactive Cell) – Denver Federal Center, CO

Installation of a Caisson Gate – Dover AFB, DE

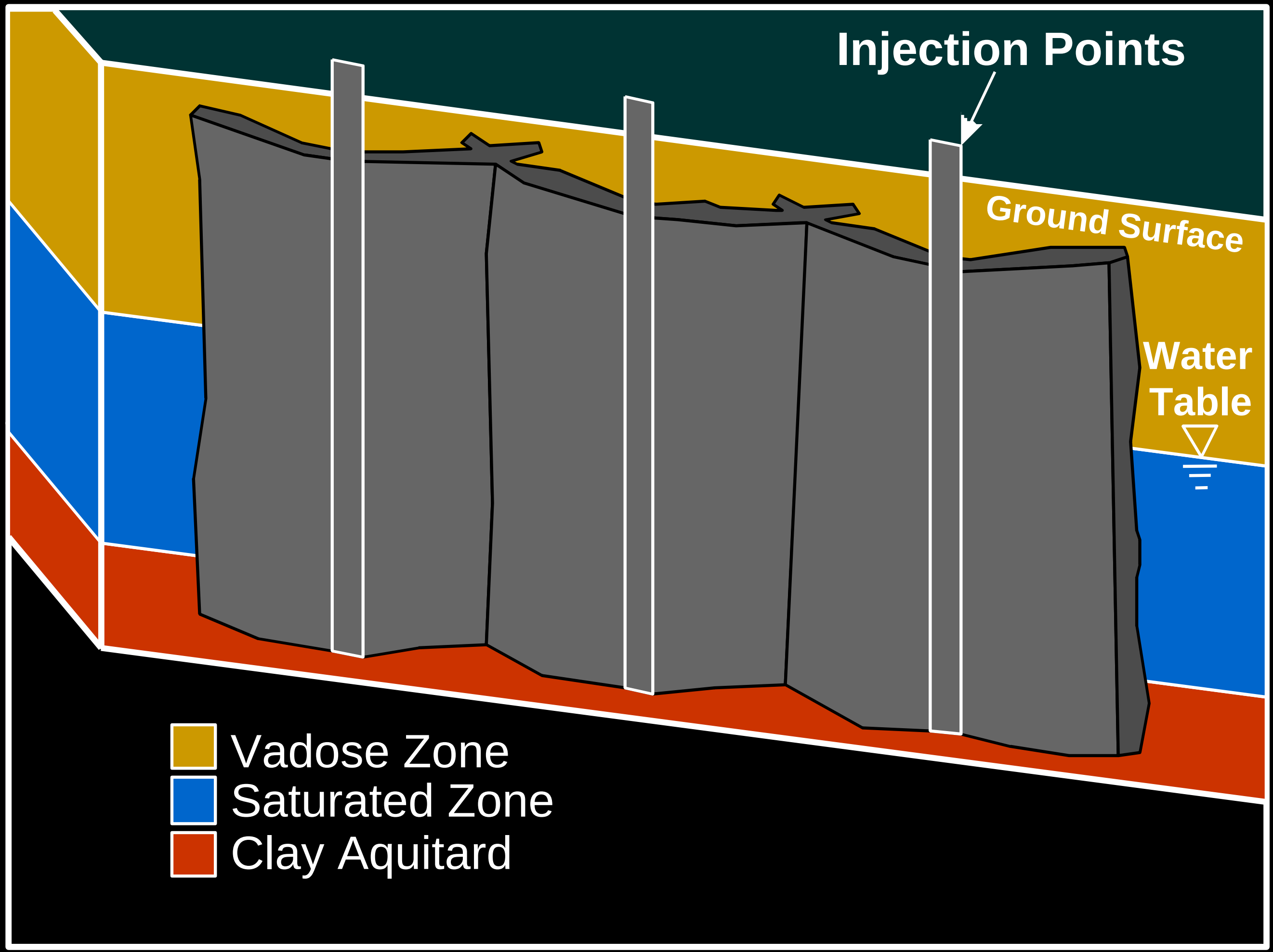
Installation of Caisson Gate

Driving Caisson with Vibrating Hammer

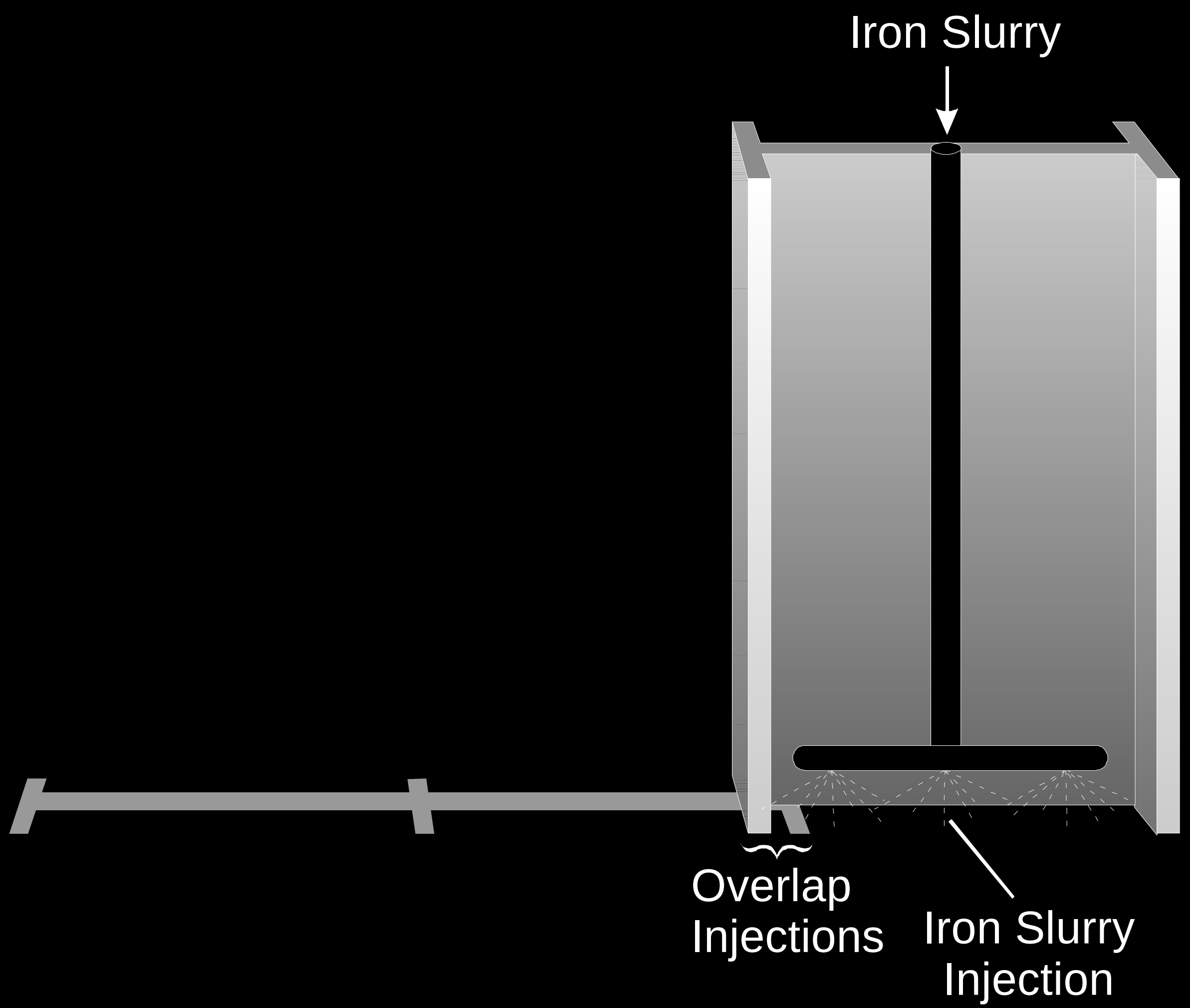
Installation by Deep Soil Mixing



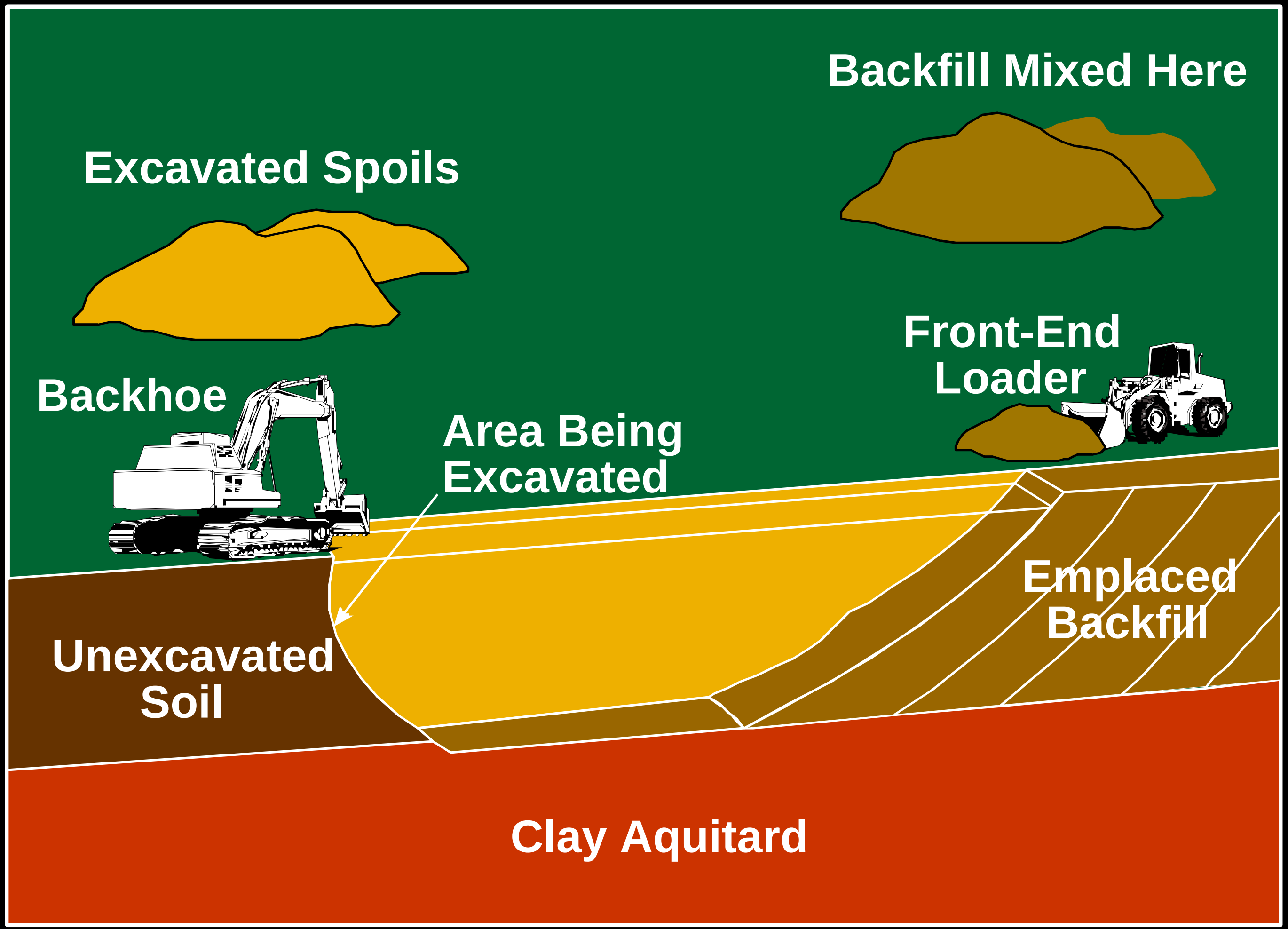
Construction by Pressure Jetting – Vertical Thin Diaphragm Walls



Vibrating Beam Cutoff Wall – Cape Canaveral, FL



Cross-Section of a Soil-Bentonite Slurry Trench, Showing Excavation and Backfilling Operations



Steel Sheet Pile Driving – Dover AFB, DE

Sealing the Sheet Pile Funnel

Driving Sheet Pile Funnel
with Vibratory Hammer

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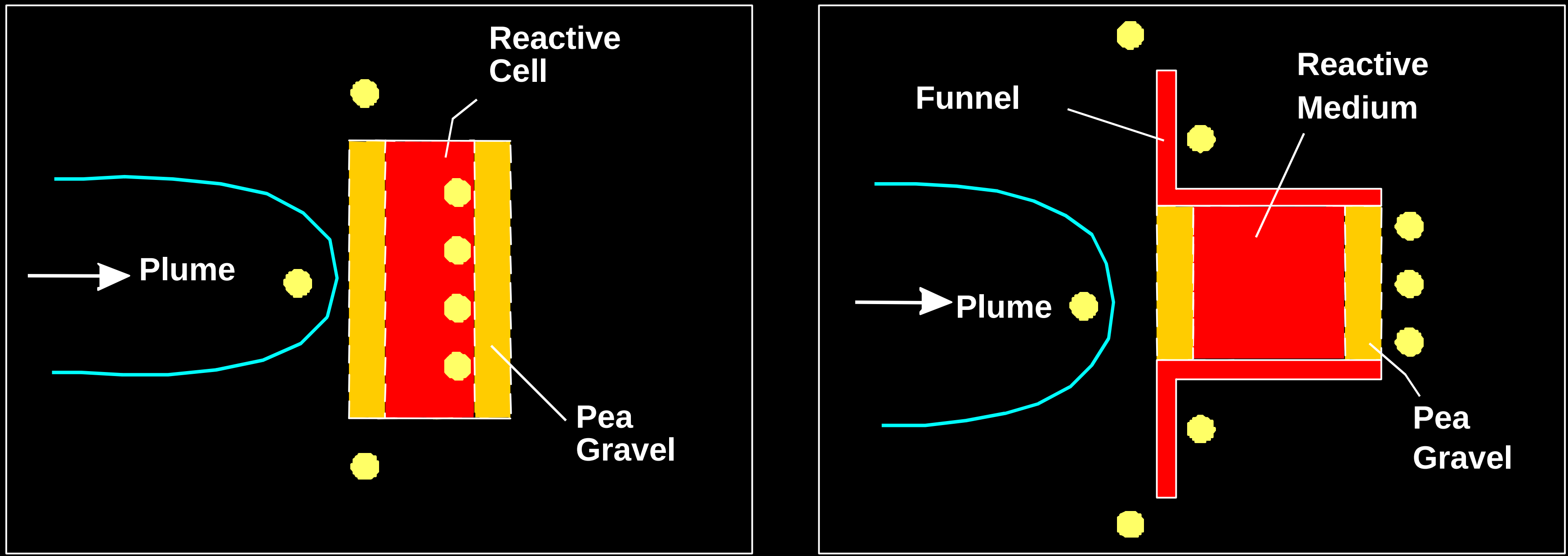
V. Monitoring the Wall

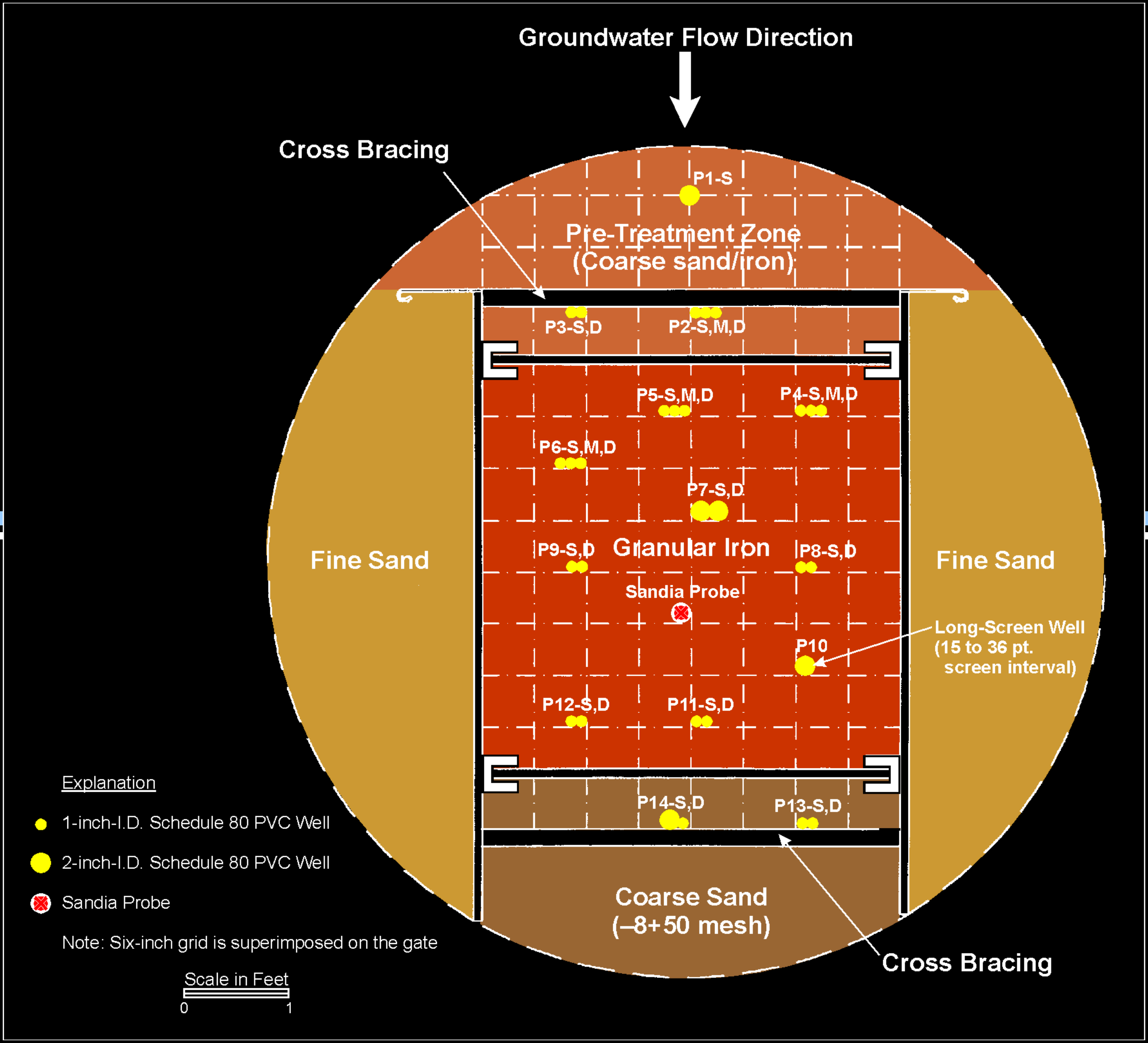
- Compliance monitoring (regulatory driven)
  - Monitoring wells on downgradient side of wall and along edges monitor for potential breakthrough and bypass
- Performance monitoring
  - Monitoring wells within the reactive medium
  - Other (groundwater velocity meters, core samples, etc.)

Typical Monitoring Well Configurations



Monitoring Well Location

Monitoring Point Network Within Gate 2 – Dover AFB, DE



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VI. Estimated Costs of a Reactive Wall

- Capital costs
  - Additional characterization
  - Treatability testing, design, engineering
  - Reactive medium ($350/ton for iron)
  - Installation
  - Technology licensing (up to 12% of materials and construction cost)
- O&M costs
  - Monitoring
  - Maintenance (currently difficult to project)

Costs from Various Sites

Site	Barrier Type	Depth	Iron Total Cost (Unit Cost)	Installation Cost
Moffett Field, CA	Sheet pile funnel, one trench gate	25 ft	$30,000 ($360/ton)	$350,000
Dover AFB, DE	Sheet pile funnel two caisson gates	40 ft	$25,000 ($350/ton)	$320,000
Denver Federal Center, CO	Sheet pile funnel 1,040 ft long, four 40-ft-long trench gates	20 ft	($375/ton)	$1,000,000
Sunnyvale, CA	Slurry wall funnel, one trench gate	20 ft	$170,000 ($650/ton)	$600,000
Elizabeth City, NJ	Continuous trench 150 ft long	24 ft	$380/ton	$350,000

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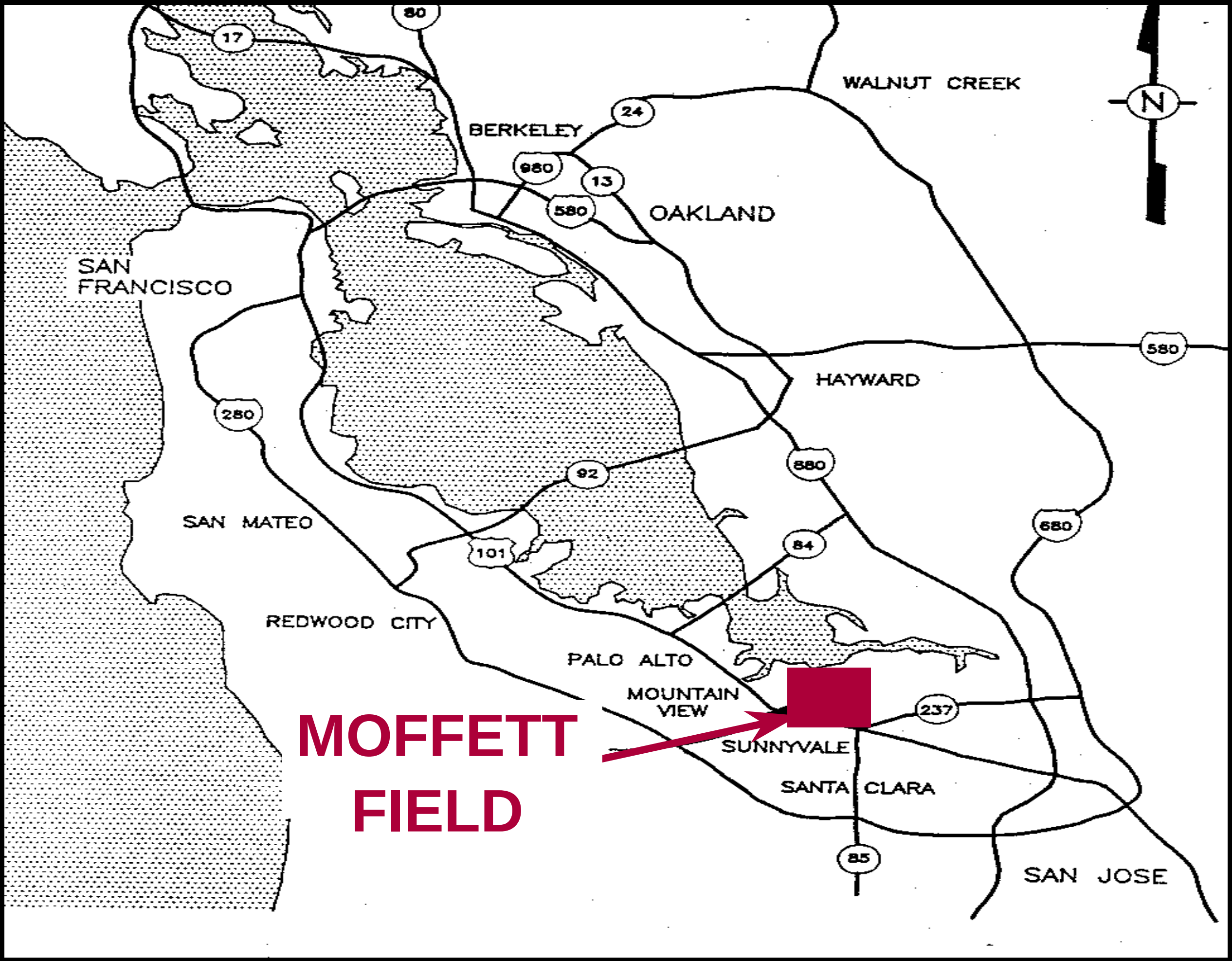
VII. Navy Demonstration Sites
Pilot Study at NAS Moffett Field, CA

- BRAC Program: U.S. Navy EFA West performed bench-scale testing, designed and installed the permeable reactive wall
- ESTCP: NFESC was tasked to collect performance monitoring and cost data, and prepare a technology transfer report for distribution to DoD and others
- 3-minute video (if time allows)

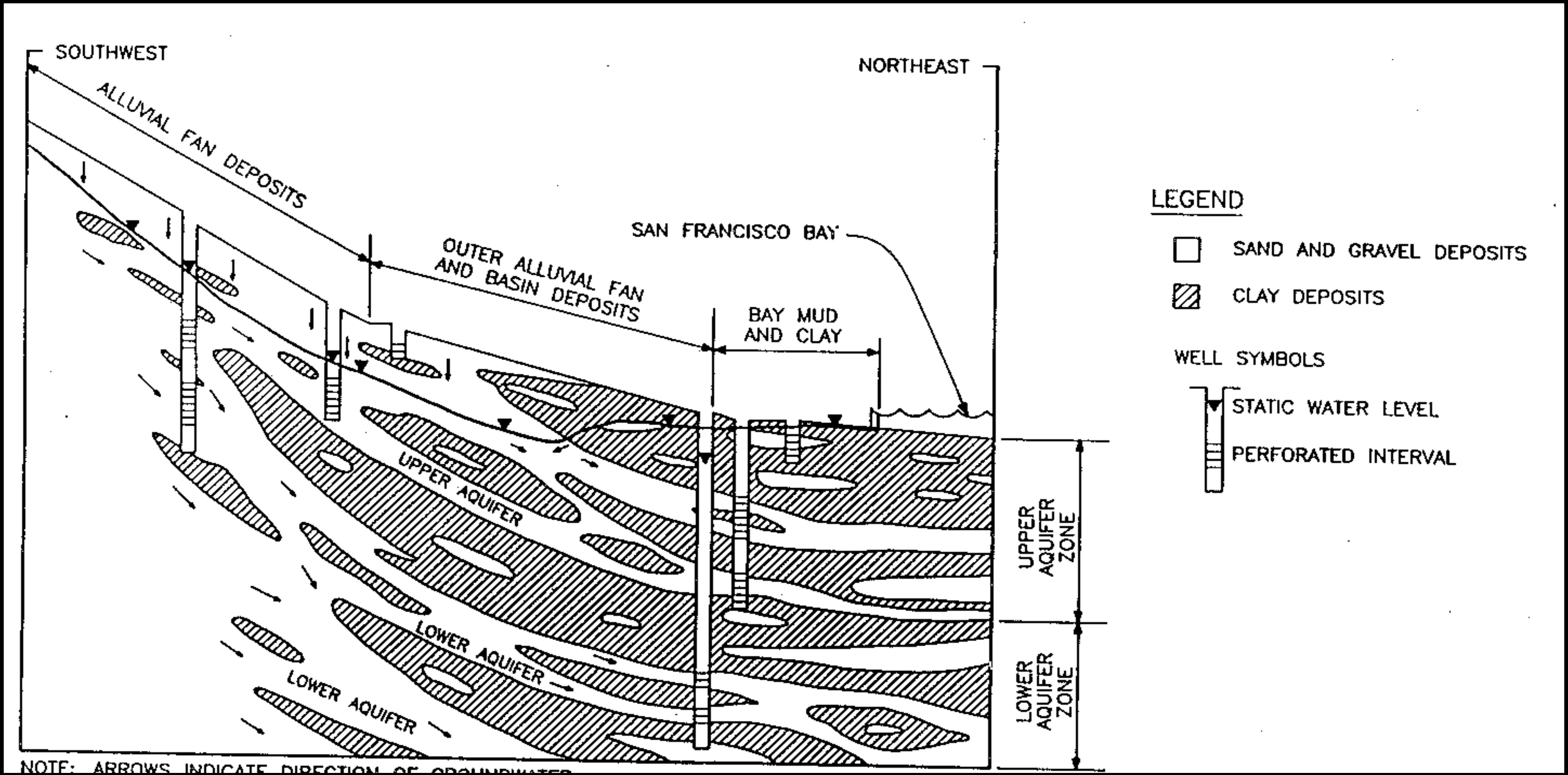
Performance Evaluation Criteria

- Chlorinated solvent reduction (water quality)
- Elevated inorganic ions (iron, chlorides)
- Production of gaseous analytes (ethanes/ethenes)
- Determine hydraulic capture efficiency and flow through the iron cell
  - Water levels (hydraulic gradient)
  - Velocity meter testing (flow rate & direction)
  - Slug/tracer testing (flow rate & direction)
  - Precipitates (chemical & biological) – coring
  - Continuous monitoring (field parameters/tracers)
  - Groundwater modeling (simulation)

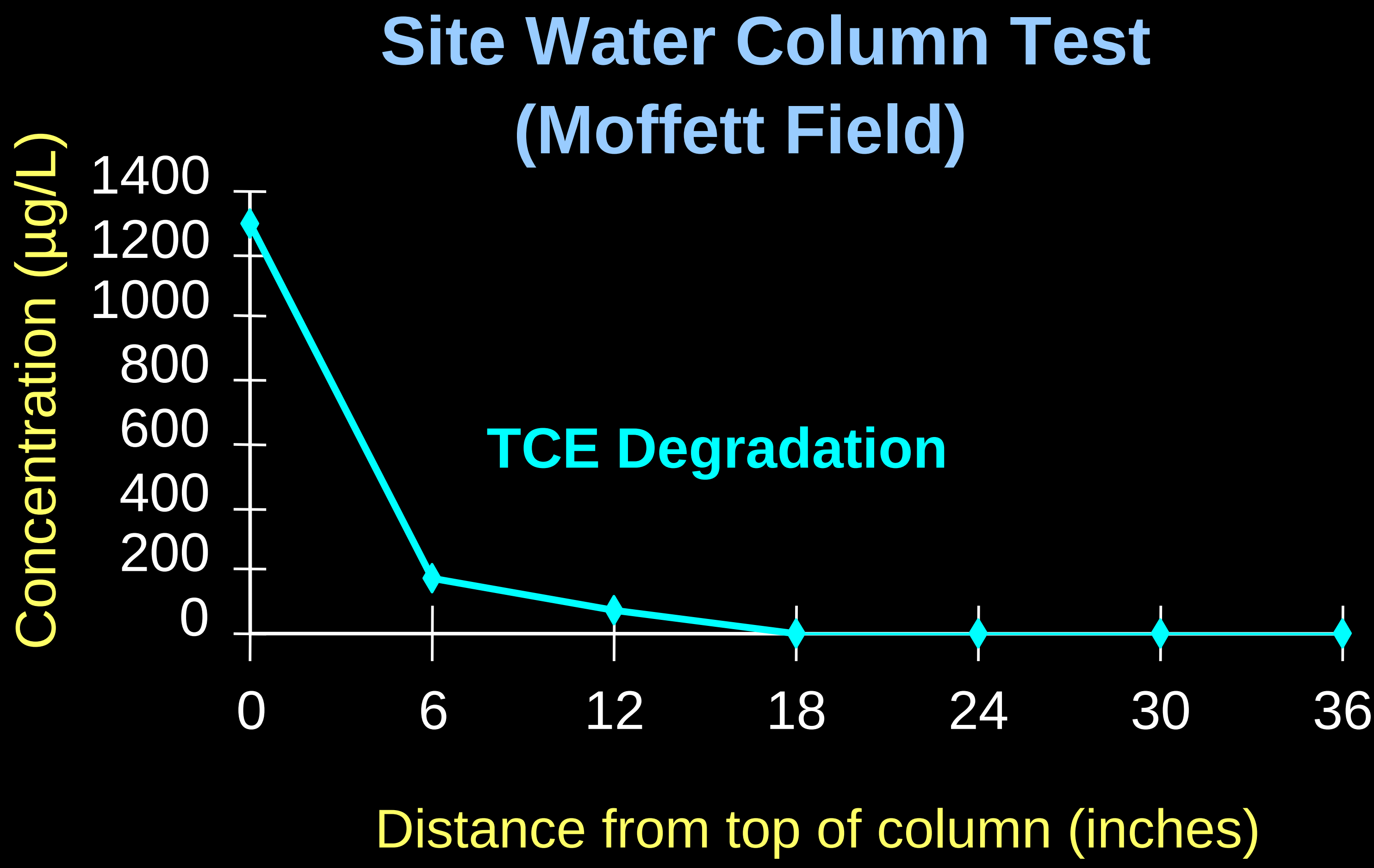
Demonstration Site Location



Moffett Site Geology



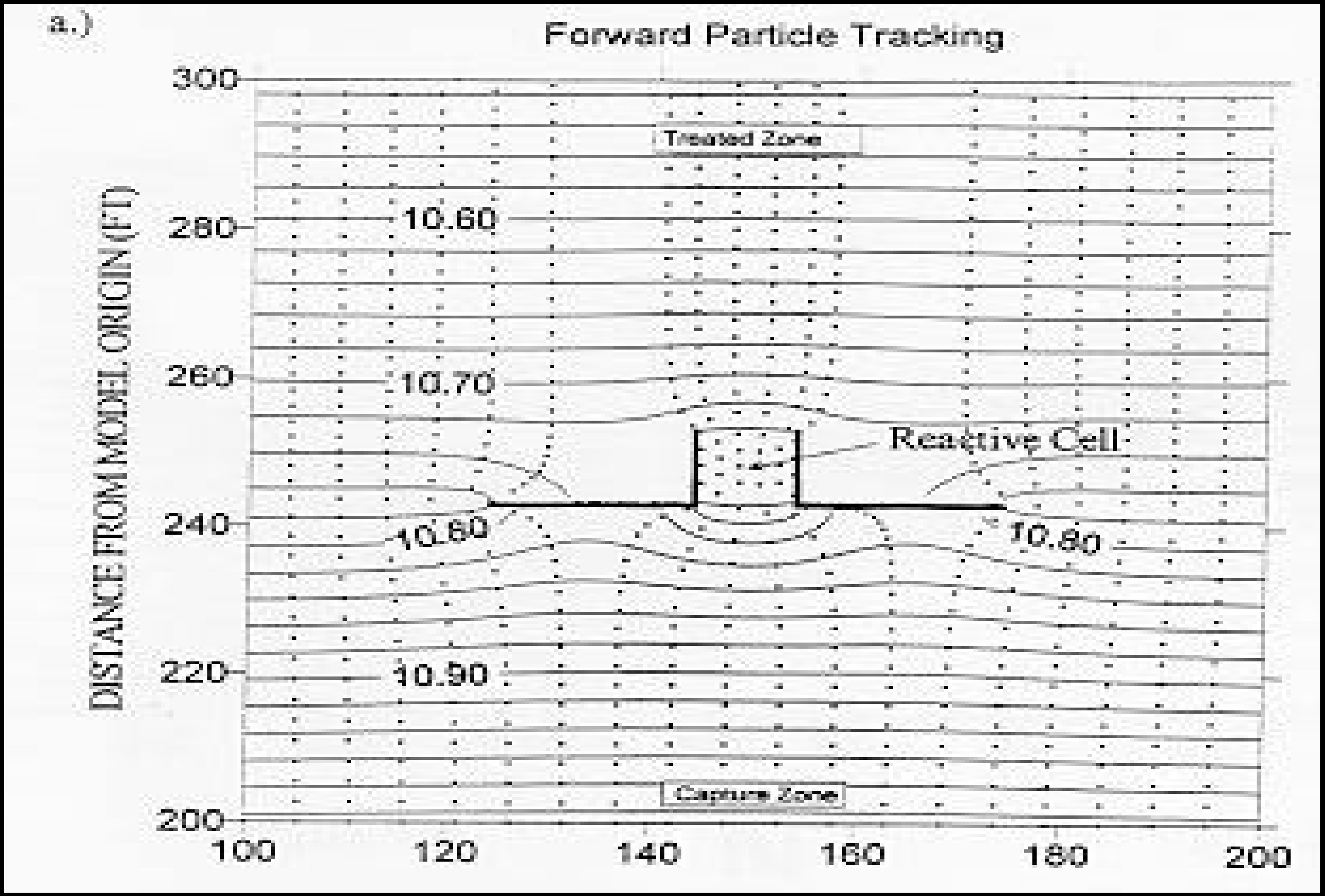
Bench-Scale Testing



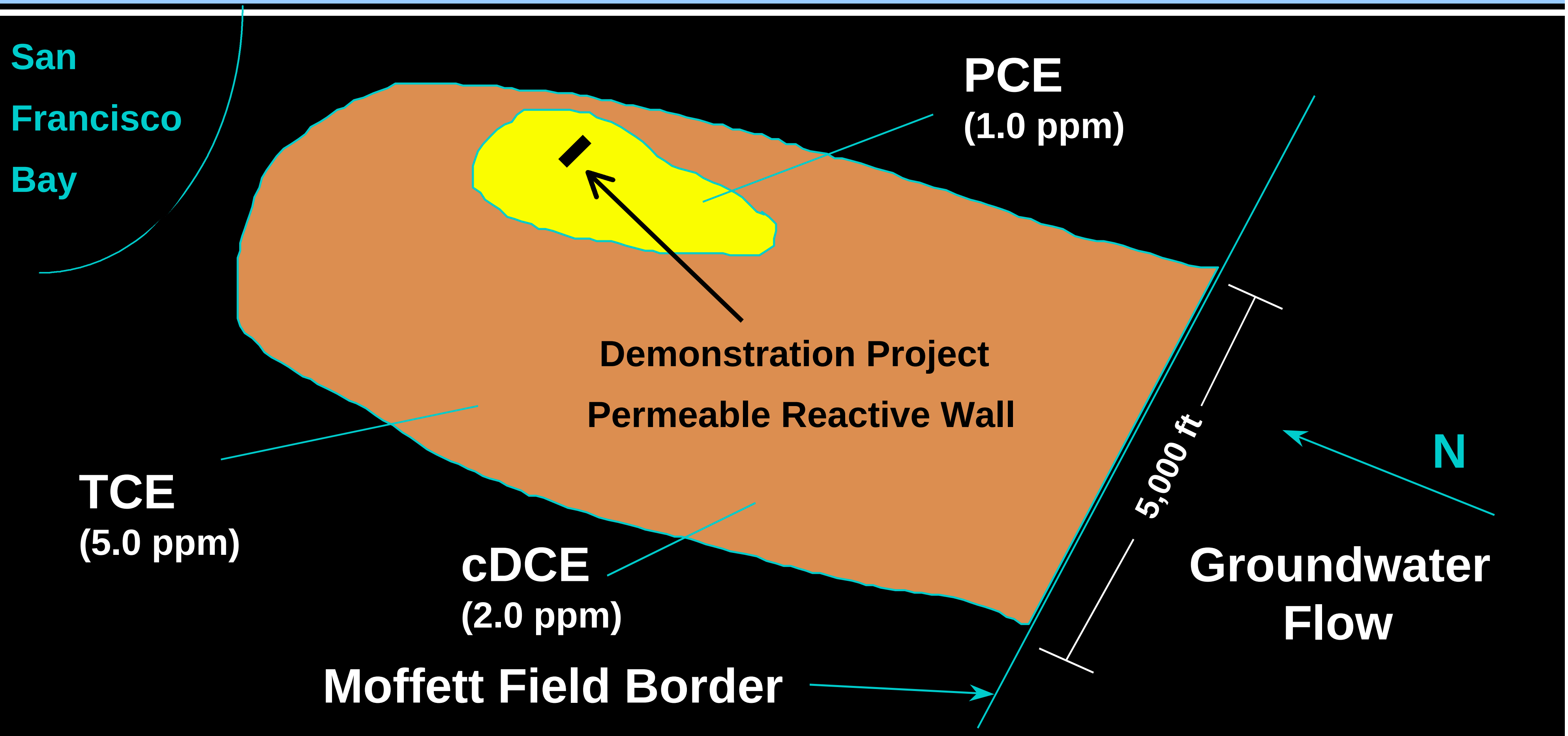
Degradation Rates from Column Tests

Compound	Half-Life (hrs)
TCE	0.6
PCE	0.3
cis 1,2 -DCE	3.1
Vinyl Chloride	4.7

Groundwater Modeling Illustration (Predicted Flow Capture)



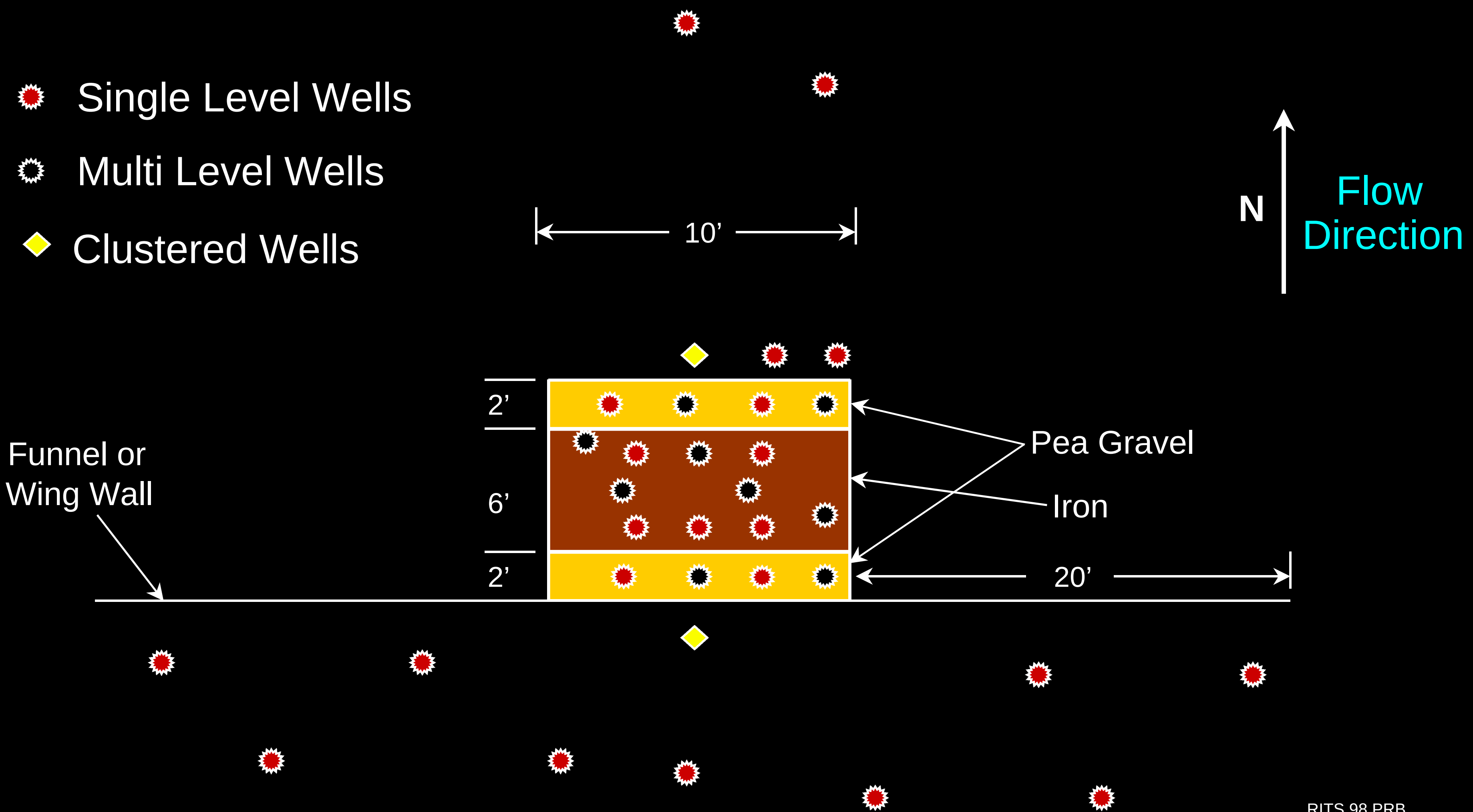
Moffett Field Solvent Plume



Funnel-and-Gate System – April 1996

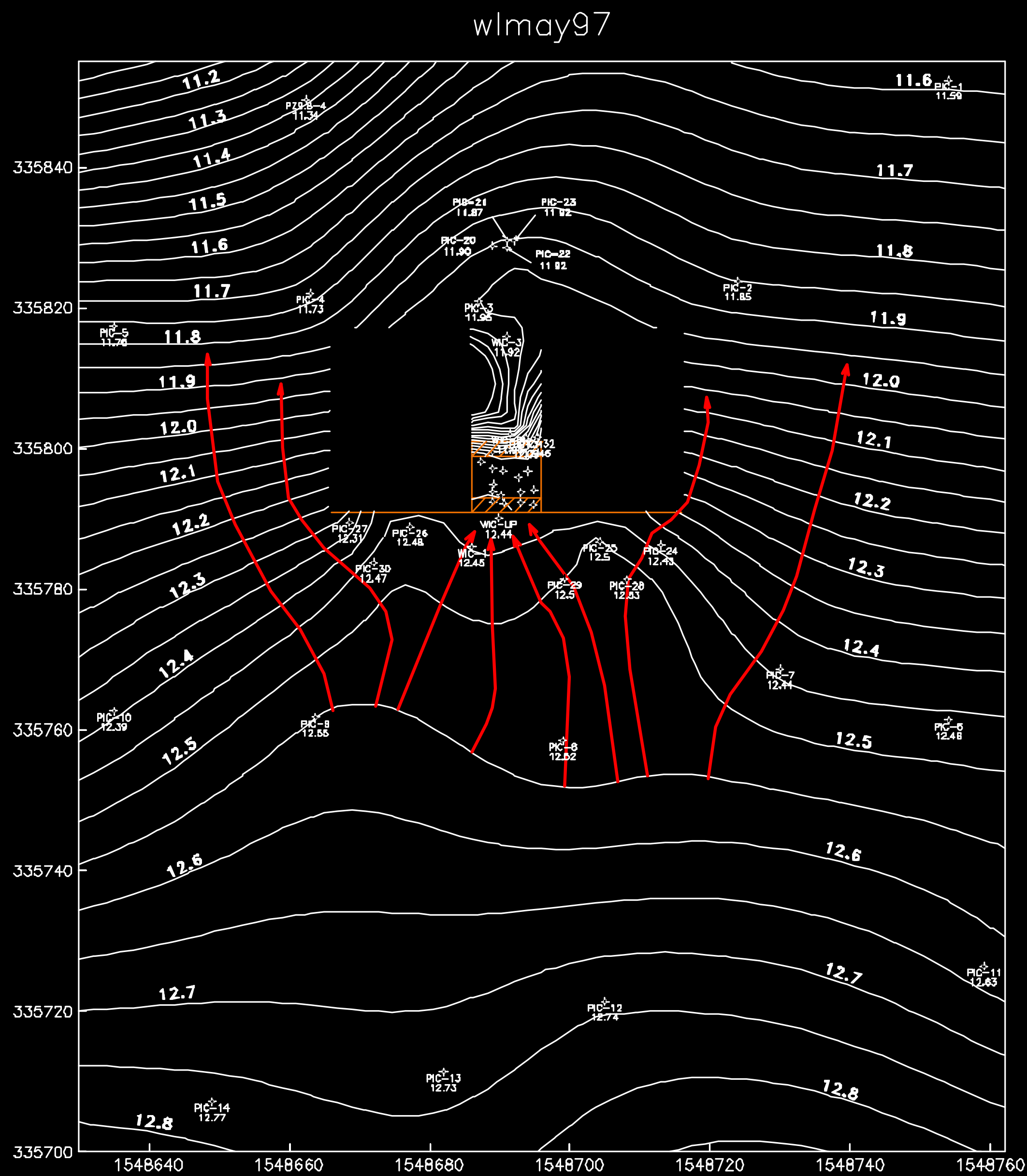
Reactive Iron Cell – Moffett Field, CA

Conceptual Diagram – Moffett Field, CA

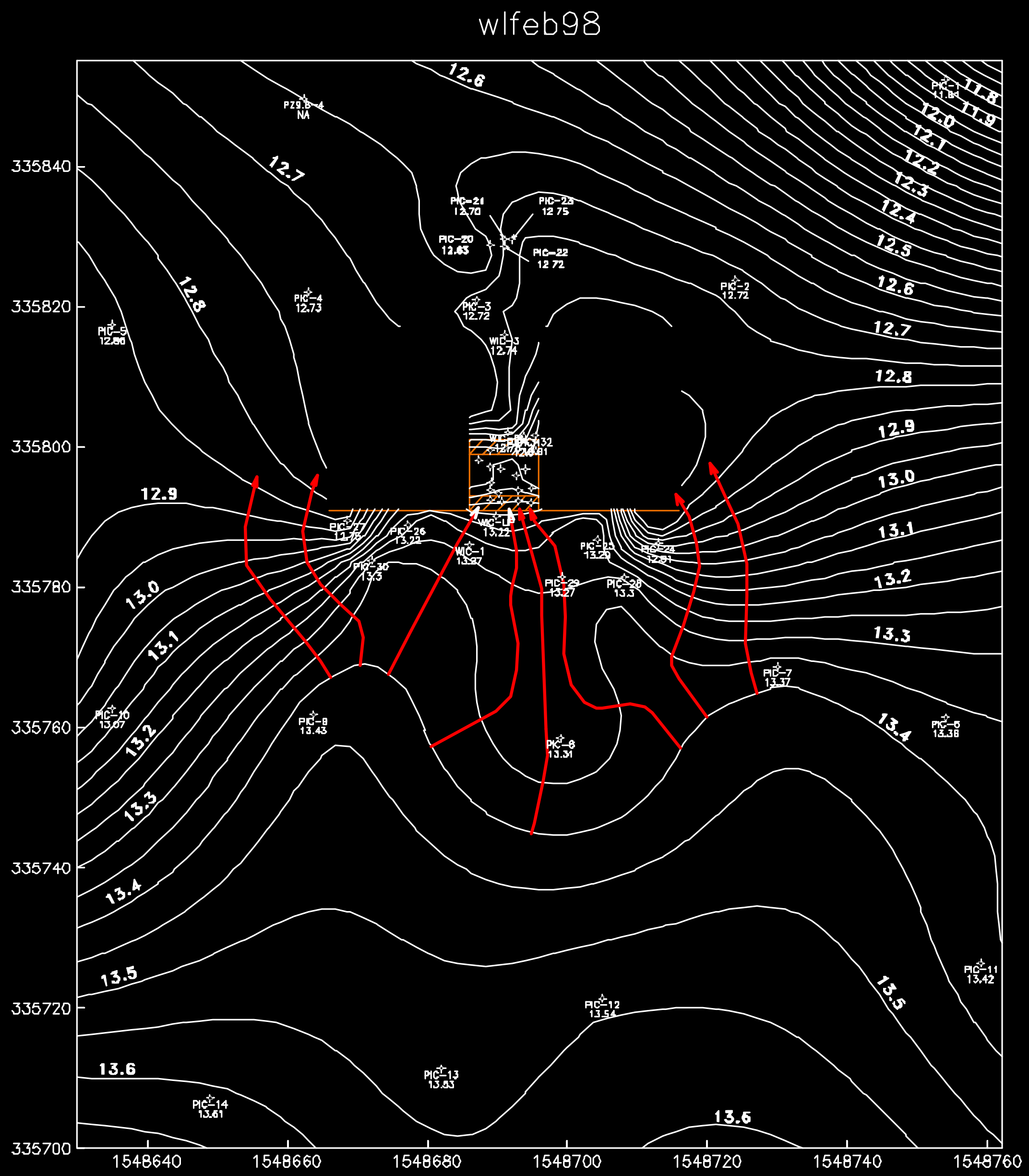


Parking Area (After Construction) – Moffett Field, CA

May 97 Water Levels and Capture Zone



February 98 Water Levels and Capture Zone



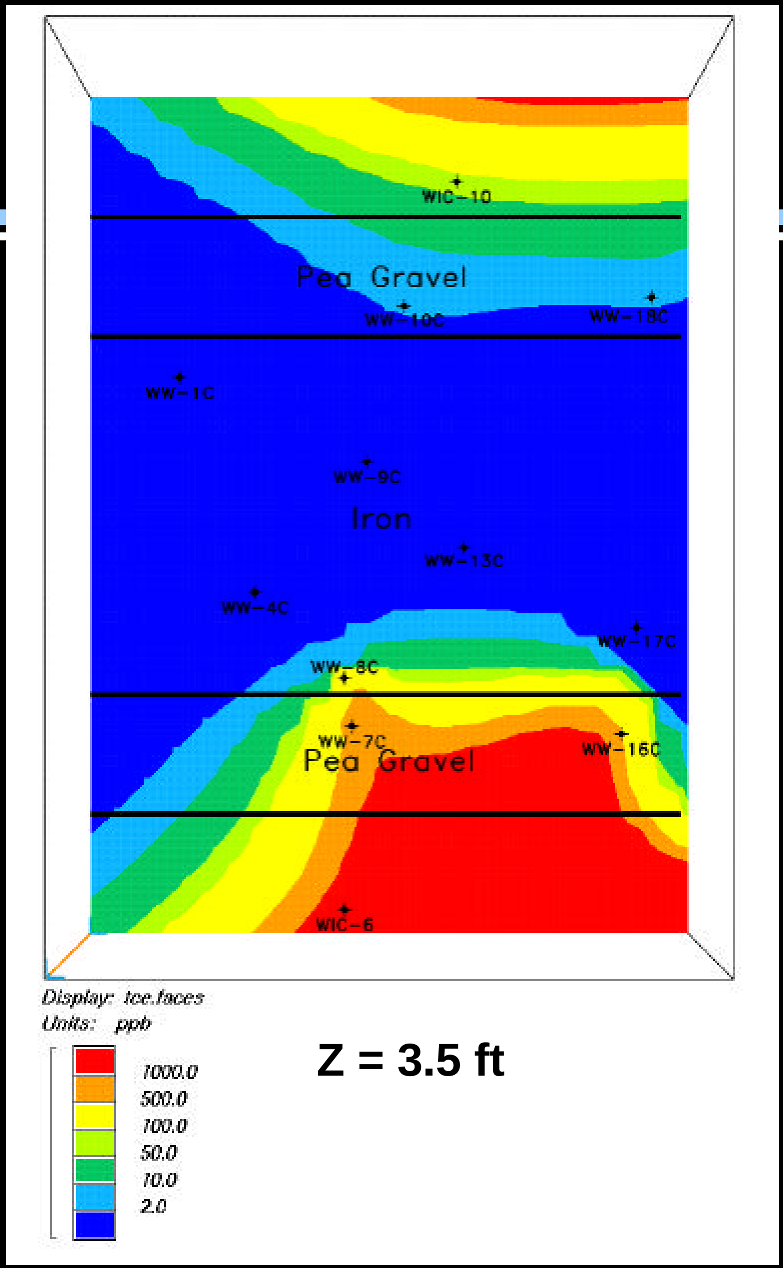
Groundwater Sampling – Moffett Field, CA

Sampling Results

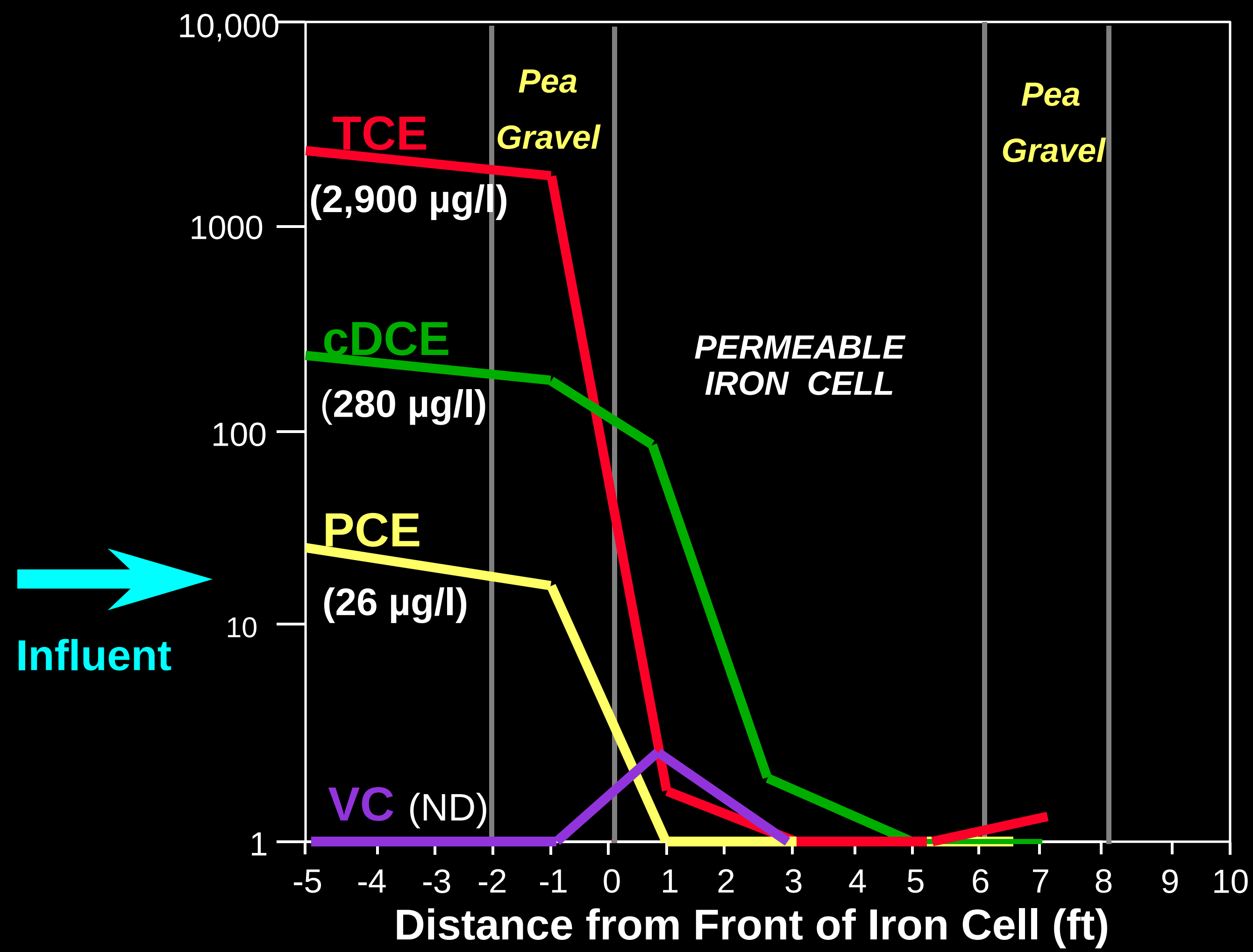
Moffett Field

January 1997

TCE Concentrations



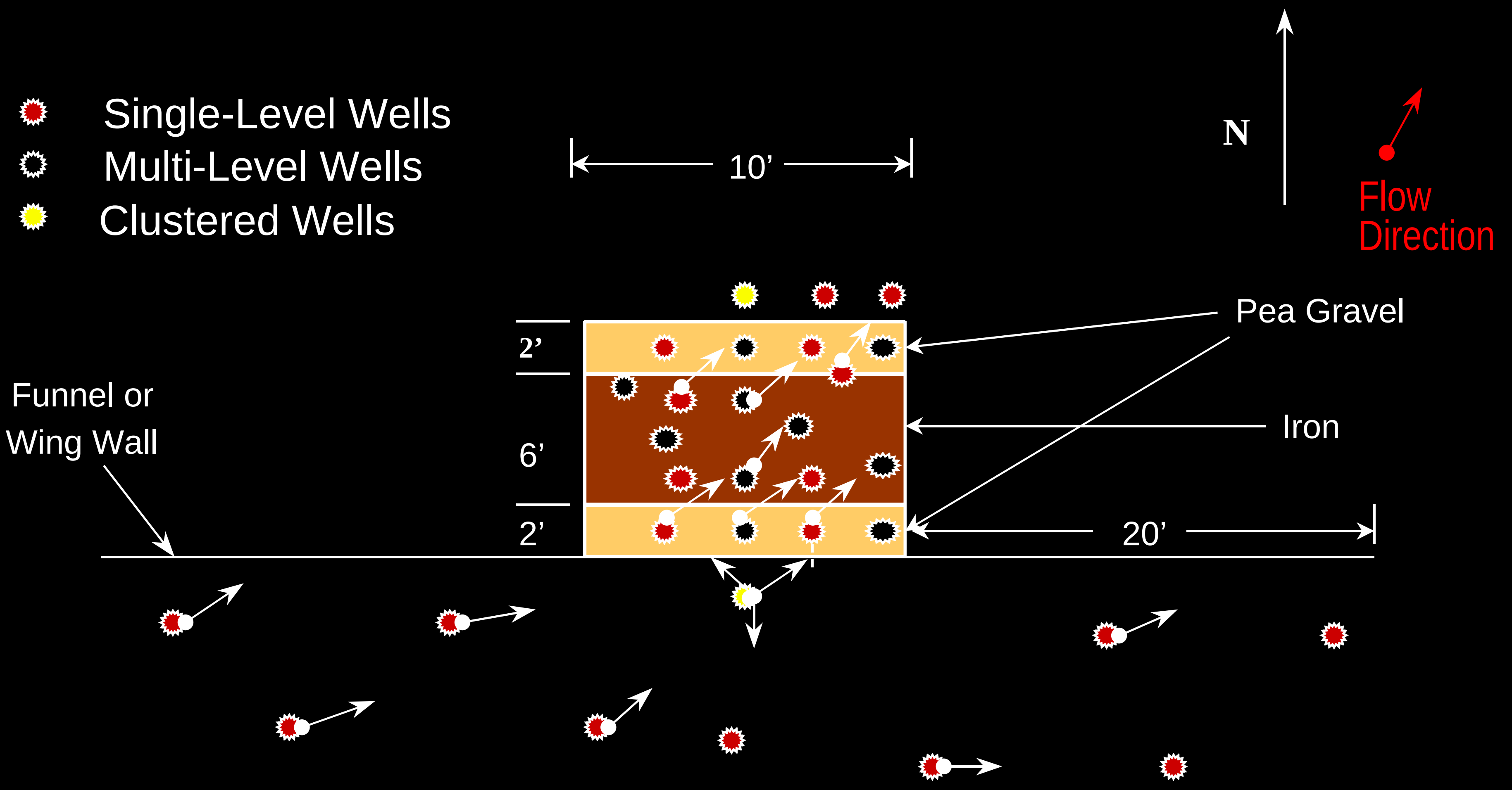
Sampling Results



Moffett Field

April 1997

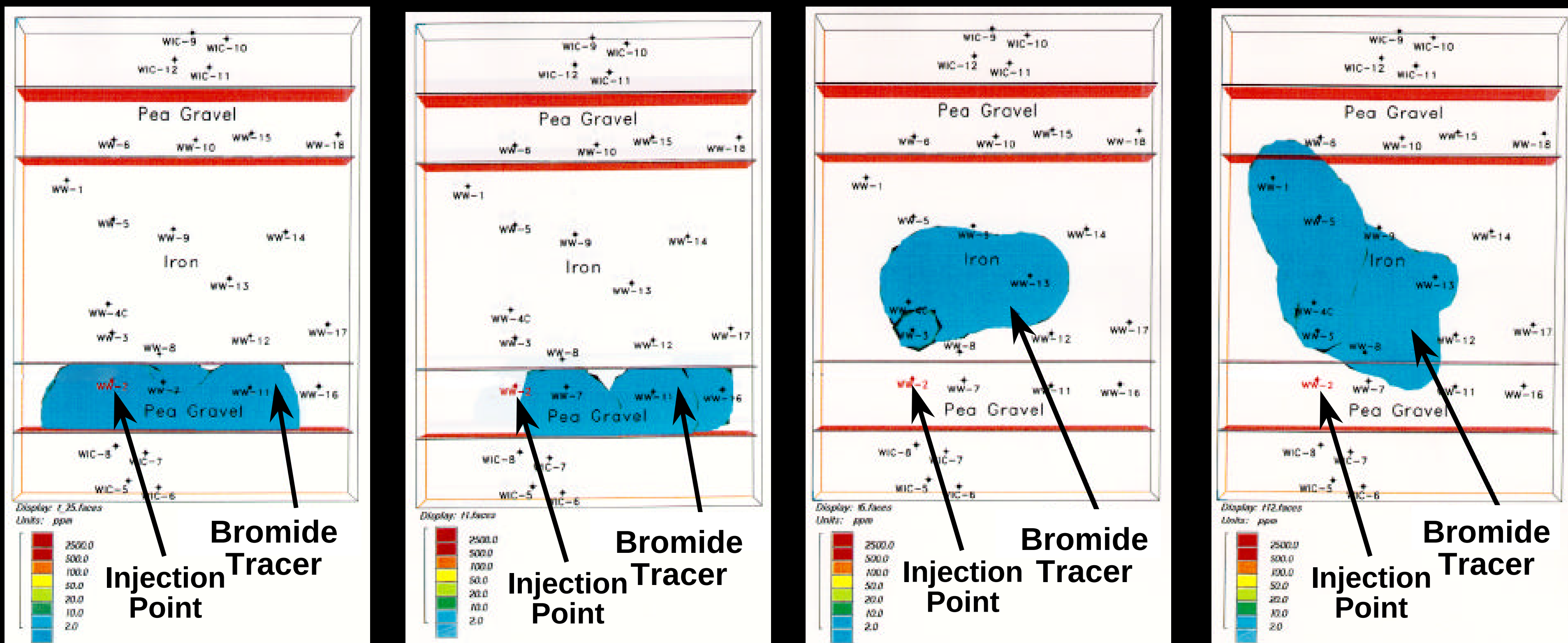
Velocity/Flow Meter Testing – Moffett Field, CA



Bromide Tracer Testing – Moffett Field, CA

Gate and aquifer injections of bromide tracers were performed to determine flow characteristics

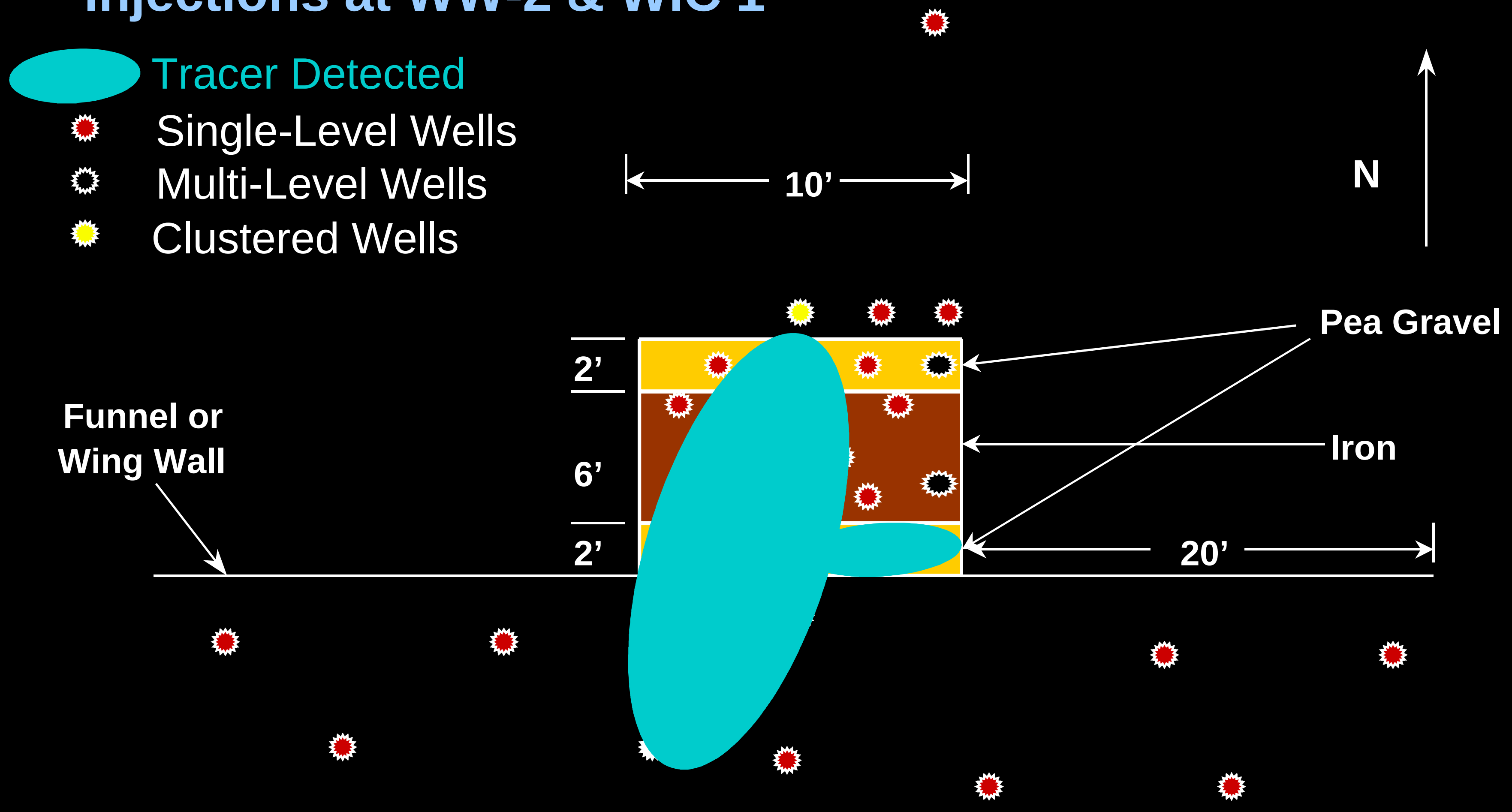
Reactive Cell Tracer Movement – Moffett Field, CA



After 0.25 Day **After 1 Day** **After 6 Days** **After 12 Days**

Tracer Testing Results – Moffett Field, CA

Injections at WW-2 & WIC 1



Iron Cell Coring –
Moffett Field, CA

Precision coring sampler

Core samples analyzed for
precipitates by RS, SEM, & XRD

Coring Results

- The analysis of the core samples indicates early signs of the types of processes predicted for the iron-groundwater interactions.
  - Oxidation of iron
  - Reduction of water
  - Precipitation of Ca and Mg minerals
  - Possibility of anaerobic microbial growth downgradient
- However, no obvious permeability or reactivity losses are apparent to date.

Moffett Field Study Conclusions (After 2 Years of Demonstration)

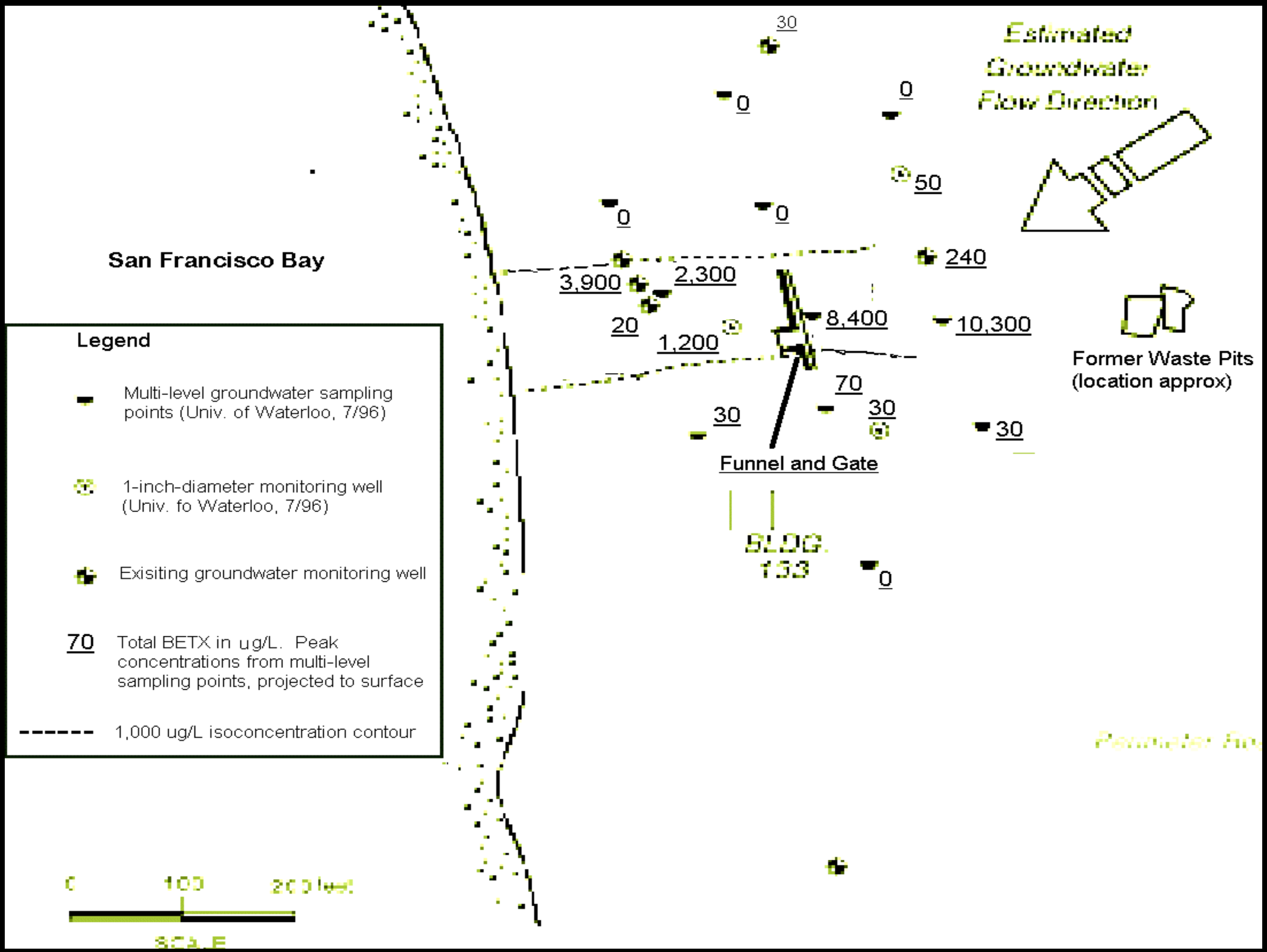
- Hydraulic results indicate groundwater flow capture
- Velocity/flowmeter testing and tracer studies show forward flow through the iron cell (1/2 to 1 ft/day)
- Water quality results indicate reduction of chlorinated hydrocarbons to below MCLs or detection limits
- Coring of the iron cell indicates the formation of some precipitates, but nothing out of the ordinary (<1%)
- Technology can be up to 4 times more cost-effective
- Final evaluation report is scheduled for August 1998

Pilot Study at NAS Alameda, CA

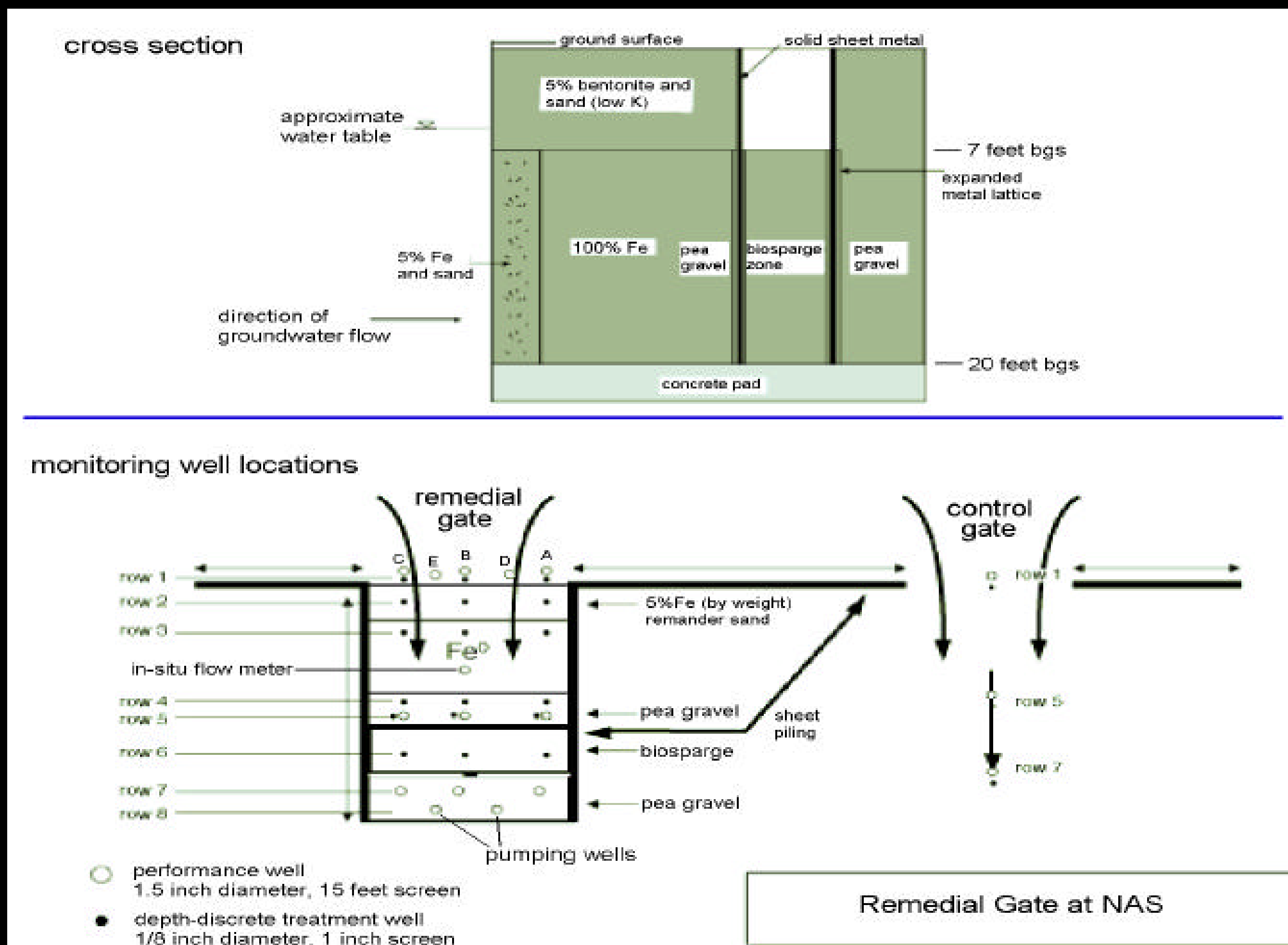
- In situ techniques for containing and treating groundwater (funnel-and-gate system)
  - Control gate
  - Iron reaction wall
  - Biosparging cell
- DoD technology demonstration grant
  - Rice University, University of Waterloo design
  - Advanced Applied Technology Demonstration Facility (AATDF) for Environmental Technology

NAS Alameda Site (January 1997)

Site Plume & Demonstration Location – Alameda, CA



Reactive Wall Design – Alameda, CA



Alameda Study Conclusions (After 1-1/2 Years of Operation)

- Chlorinated compounds were significantly reduced (>90%), but not eliminated
- The contaminant plume spatially variable and no dispersion zones present; hence, contaminant breakthrough occurred
- The biosparge zone supported further aerobic degradation of the VOCs (incl. BTEX)
- Using granular iron with biosparging can be an effective alternative (Univ. of Waterloo)

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VIII. PRW Technology Summary

- Permeable reactive walls work well in remediating groundwater contaminated with chlorinated solvents and some metals (hexavalent chromium)
- Usually more cost-effective than pump-and-treat
- Keys to success are in proper design and deployment
- Longevity issues are not yet well defined
- Research is being conducted on using bimetals

NFESC Technology Application Team
Permeable Reactive Walls

- Team Leader: Chuck Reeter
- Team Members: Jed Costanza, Steve Fann, Martha Gonzales, Kathy Greene, Mark Kram
- Objectives and Services
  - Technology Transfer
  - Project Management & Assistance
  - Technical Papers, Posters, Conferences, Seminars
  - Training (RITS, CECOS)
  - Technology Promotion (RTDF, ITRC, ESTCP, SERDP)

NFESC Points of Contact

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Permeable Wall References

- *Design Guidance for Application of Permeable Barriers to Remediate Dissolved Chlorinated Solvents.* Prepared by Battelle, Columbus, Ohio for Environics Directorate, U.S. Air Force. February 1997.
- *Performance Monitoring Plan for a Pilot-Scale Permeable Barrier at Moffett Federal Airfield.* Prepared by Battelle for NFESC. July 1997.
- *Regulatory Guidance for Permeable Barrier Walls Designed to Remediate Chlorinated Solvents,* ITRC. September 1997.
- Others (EPA, DOE, RTDF, Univ. of Waterloo, etc.)